VŠB – Technical University of Ostrava
Faculty of Electrical Engineering
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Cable Sizing Calculations in Industrial Installations
Dimenzování kabelů v průmyslových instalacích

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Faculty of Electrical Engineering and Computer Science
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Diploma Thesis Assignment

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- Importance and criteria of correct cable sizing
- External factors having impact on cable sizing (laying methods, ambient temperature, environment, etc.)
- Algorithm creation for cable sizing according to IEC 60364-5-52 and its implementation in chosen software tool
- Verification of the correct functionality of the created algorithm on practical examples

References:

• Whitaker, J. C.: AC Power Systems, CRC Press 1991
• Burke J. J.: Power Distribution Engineering: Fundamentals and Applications, New York, 1994
• Machowski, J., Bialek, J., Bumby, J.: Power System Dynamics and Stability, Chichester, 1997

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

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VYSOKÁ ŠKOLA BÁŇSKÁ-TECHNICKÁ UNIVERZITA Fakulta elektrotechniky a informatiky 1D16 * OSTRAVA *

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Declaration Made by the Student

I hereby declare that this master's thesis was written by myself. I have quoted all the references I have drawn upon.

Date: 12.05.2020

Signature:

Abstract and Keywords

Abstraktní

Správný výpočet u dimenzování zařízení hraje klíčovou roli při návrhu instalace. Špatný návrh zařízení může vést k jeho abnormální funkci, případně k dalším vážným následkům. Tomuto problému se čelí při dimenzování kabelů nízkého napětí. Kabely nízkého napětí představují hlavní část distribuční sítě, která napájí koncové spotřebitele, a proto jsou velmi důležité pro stabilní chod sítě.

Hlavní dokument zabývající se výše uvedenou problematikou je norma IEC 60364-5-52. Norma obsahuje mnoho doporučení, odkazů na jiné normy a nemá ucelenou strukturu, co se týče podmínek, které mají být splněné pro správný návrh kabelů. Účelem této práce je objasnit hlavní body této normy, navrhnout algoritmus pro správný návrh kabelů nízkého napětí a demonstrovat správnost navrhnutého algoritmu na příkladech.

Klíčová slova

Kabel, korekční faktor, průřez, proud, proudová kapacita, dimenzování, porucha, instalace, LV, referenční metoda, dimenzování, zkrat, teplota, nástroj.

Abstract

Correct calculations or sizing of any device or equipment plays significant role in design of installation. In case of wrong design, it could lead to abnormal operation of installation or even worse consequences. This problem could be faced during sizing (choosing appropriate cross-section) of low voltage (LV) cables. LV cables present the major part of distribution network which supply end consumer and since then they are the very important part in stable operation of network.

The main document which regulates aforementioned question is IEC 60364-5-52. However, it consists of many recommendations, references to other concern standards and has no clear structure of conditions which shall be fulfilled for correct dimension of cable. Purpose of this thesis is to explain main statements of mentioned standard, suggests simplified algorithm of correct dimensioning of LV cables even for not specialized person and shows examples of its correctness.

Keywords

Cable, correction factor, cross-section, current, current-carrying capacity, dimensioning, failure, installation, LV, reference method, sizing, short-circuit, temperature, tool.

Table of Contents

List of Symbols and Abbreviations Used

ABB - Asea Brown Boveri;
EPR - Ethylene propylene rubber;
FEM – Finite-Element Method;
FTB – Fluidized Thermal Backfill;
HDPE – High-Density Polyethylene;
HV –High Voltage;
IEC – International Electrotechnical Commission;
LV – Low Voltage;
MV – Medium Voltage;
MS - MicroSoft
PVC – Polyvinyl Chloride;
RMS – Root Mean Square;
SBM – Sand-Bentonite Mixture;
ShC – Short-circuit Current;
THD – Total Harmonic Distortion;
VBA – Visual Basic Applications;
XLPE – Cross-Linked Polyethylene

List of Images and Charts

Introduction

Nowadays selection of the cables is inalienable part of design of any type of installation. Without correct choice of cross-section of cable, it is not possible to achieve reliable operation of the network as wrong selection could lead to high power losses and voltage drops, inappropriate selection of protection devices, higher ratings of short-circuit currents, overloading, outage of equipment which could cause economical losses, increasing of breakdown rate of the network, lethal exoduses and etc. Therefore, it is necessary to sort out in details what stands behind of such calculations: theory of physical processes which occurs in cables during normal and abnormal operations, - what is the correct algorithm of selection of the cable, which standards regulate this topic and considering all consequences which could come from those statements. This thesis was made to find and describe answers for aforementioned questions.

Chapter 1 consists of statistics of content of networks with LV and MV cables, analysis of failures which happened either due to cable failure or related to cable reason. However, the main purpose was to describe the general steps which shall be followed for correct selection of the cross-section of the cable and consequences of not following to them.

Chapter 2 describes theoretical background of the dimensioning of the cable, what IEC 60364-5-52 Standard declares regarding this topic, which recommendations and rules it consists of. Based on sorted statements from standard were given explanations to them in terms of physical processes which occurs in cable during operation, which aspects shall be considered and not be neglected during selection of cross-section of the cable. Hence, was suggested the theoretical algorithm and built flowchart which describe step by step actions to be followed during dimensioning of the cable considering IEC 60364-5-52 Standard and related literature.

Chapter 3 describes practical algorithm which was developed and simplified during work on chapter 2 and implemented in MS Excel by means of Visual Basic Applications as a tool. Its purpose is simplification of dimensioning process for user by means of substitution of work with relevant tables and formulas taken from different standards and books but just to collect input data, correctly to fill it in and collect the result. Besides description of practical algorithm there is presented an overview of a tool.

Chapter 4 consists of practical examples which shows different working aspects of the tool, represent its functionality, explanations to the obtained results and suggestion of possible improvements in the tool.

1 Importance and Criteria of Correct Cable Sizing

1.1 General information

The power grid is defined as a critical infrastructure and a total outage of the grid would affect the life of the majority of the population and could result in a national crisis if the outage is not resolved fast. The main aim of power grid of Czech Republic is to supply electricity to over 4.4 million households [1]. The low voltage (LV) grid had no priority due to small amounts of failures in comparison with medium voltage (MV) and high voltage (HV) grids. The Czech Republic power grid consist of the following grids:

- Transmission grid (400, 220 kV);
- Subtransmission grid (110 kV);
- Distribution and industrial grid (3*, 6*, 10*, 22, 35 kV);
- Most of the customers are connected to the power grid by the LV grid of 0.4 kV.

Underground cables are a fundamental element in any energy system, as they allow energy to be transported and distributed to consumer points. From Table 1 and Figure 1 could be seen that total length of LV underground cables in comparison with other types of lines within Czech Republic has a tend to increase with years [2]. It could be described as expanding of a regular and industry sectors which must be connected to the power grid.

Therefore, if cables fail, it could cause inconvenience for both:

- Consumers, who will not have their energy supplied;
- Operators, who will have their quality of service indicators affected.

For this reason, it is important to access cable behavior in order to make asset management decisions, either to replace or refurbish existing cables.

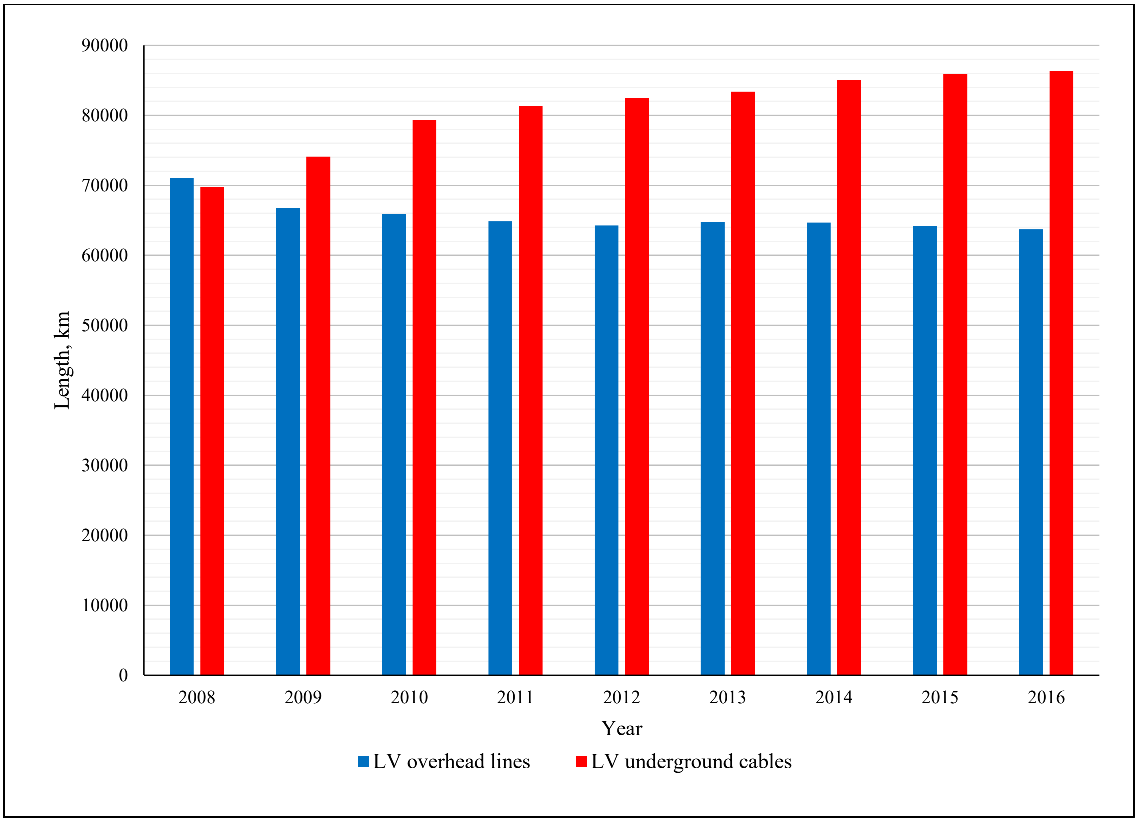


Figure 1 – LV lines length evolution

* - not maintained, continuously being replaced by 22 kV network

	2008	2009	2010	2011	2012	2013	2014	2015	2016
Overhead lines – MV, km	60,821	60,226	59,394	59,417	59,029	58,990	58,950	58,920	58,885
Underground lines – MV, km	15,502	16,201	16,688	17,056	17,158	17,514	17,865	18,034	18,137
Total	76,323	76,427	76,082	76,473	76,187	76,504	76,815	76,954	77,022
Overhead lines – LV, km	71,083	66,750	65,849	64,886	64,274	64,709	64,687	64,239	63,727
Underground lines – LV, km	69,735	74,102	79,376	81,335	82,466	83,375	85,071	85,935	86,328
Total	140,818	140,852	145,225	146,221	146,740	148,084	149,758	150,174	150,055

Table 1 – Length of MV and LV overhead lines and underground cables

1.2 Failures in LV networks due to cable failures

Cable failure is a rising concern among utilities, particularly underground cables, as they are harder access and are more costly to replace, as their installation is ten times higher than overhead lines [3].

Currently utilities are experiencing some information gaps regarding historical cable failure information [3]. In other words, in the past there has been a general neglect or deficient information of underground failures.

However, nowadays the monitoring of the LV grid is still limited in comparison to MV and HV grids and it can therefore be a problem to derive relevant data for further researches. But some countries (Sweden, Germany, Denmark, Portugal and etc.) hold such articles in free access in the Internet. So, further statements are relied on researches [3],[4],[5].

Based on the failure data from failure reports spanning from January 2010 to January 2018 retrieved from Ellevio’s database [4] there are in total 7064 reports where the cause of failure is reported as cable related (according to [3], cable failures are responsible for 10% - 50% of all incident). A failure is generally reported, when one or more customers have noticed an outage and notified the network operator. During 2016 the system for reporting failures changed, that means that failure reports may differ before and after 2016 The amount of failures which were registered as “cable failures” mentioned in Figure 2. As it could be mentioned, amount of failures with years keep almost the same value and it could be described as during 2016 the system for reporting failures changed, that means that failure reports may differ before and after 2016.

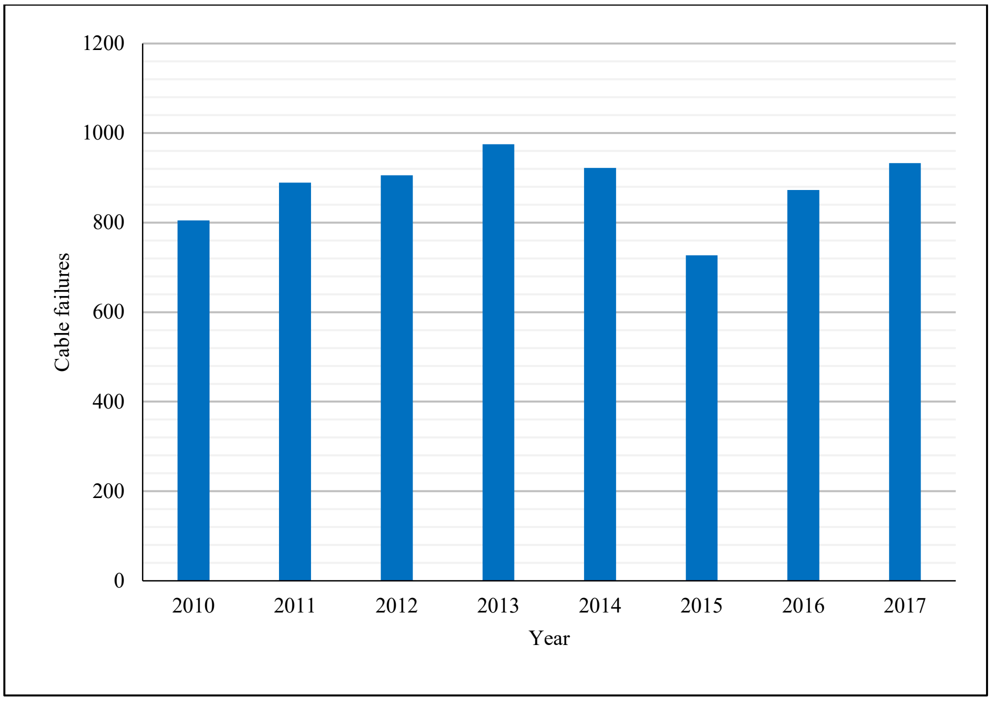


Figure 2 – Reported cable failures

In article [4] were specified reasons due to which failure connected to cable failure occurred. The occurrence of cable related failures is presented on Figure 3.

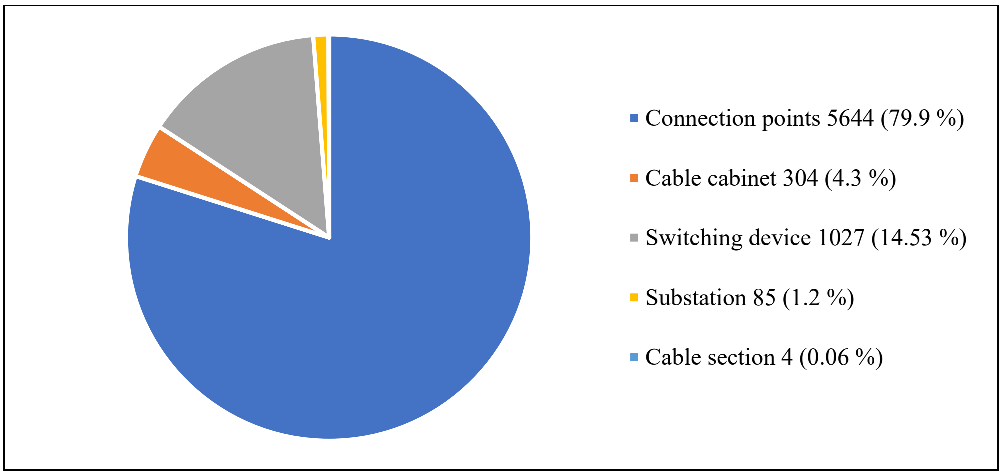


Figure 3 – Occurrence of cable related failures [4]

Unfortunately, in mentioned article are not described the exact reasons of failure, only general aspects are given due to time demanding analyzing of reports [4]. Within all failures there are 304 (4.3 %) failures which could be interpreted as failures due to insulation fault or material ageing. Sometimes such failures happen with new design cables, what means bad design and dimension of cable.

In article of German researches [5] are presented results of analyses based on Vattenfall Distribution company failure reports from Sweden of LV distribution equipment during the period from 2004 to 2008. The causes of LV underground cable failures that caused long duration customer outages over 6 hours during 2004-2008 are presented in Table 2.

Based on above mentioned data, it could be noticed that again the main reason of failures of LV underground cables is due to material failure, in other word, ageing-related faults and insulation faults.

Failure cause	Number of failures	Percentage (%)
Tree fall, wind	145	12.4
Wind and thunderstorm	23	1.9
Tree fall, snow	15	1.3
Snow, ice load	11	0.9
Material failure	654	55.8
Traffic	30	2.6
Animal	2	0.2
Tree felling	2	0.2
Fuse blow	11	0.9
Lack of maintenance	3	0.3
Dig in	180	15.4
Wrong montage	16	1.4
Sabotage	4	0.3
Unknown	57	4.9
Other	19	1.6
Total	1172	100

Table 2 – Cause of LV underground cable failures

In article of Portuguese researches [3] are presented results of significant analyses of reliability of MV underground cables for Portugal. Even if these results are related to MV it is still possible to use common received information regarding underground cable as a good example. The MV cable failure causes are represented in proportion in the Figure 3. Again, the most failures (68%) in cables are due to the equipment itself, mainly because of insulation faults (84%) and material ageing (15%).

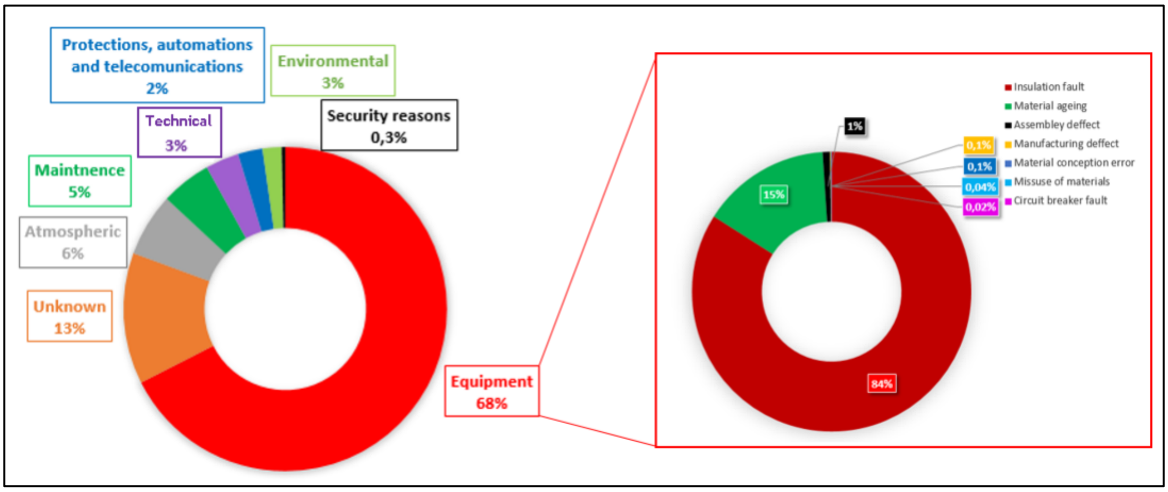


Figure 4 – Underground cable failure [3]

To sum up, above mentioned information serves as one of examples why it is important to design cables correctly and consider many factors, which will be described in further chapters. Length of LV underground cables is significant as the LV network serves for power supply of end consumers. Without a doubt it is possible to state that amount of failures is significant throughout of countries even with developing of technologies and more attention to LV networks. According to above mentioned graphs and tables, it could be observed that almost all failures of cables are caused by insulation break or ageing. The statement: “It happens only because of abnormal conditions or because of time being” – is wrong, there is presented human factor for sure, in other words, wrong design, montage and etc.

To avoid such a problem with collecting of information regarding failures in article [3] it is described a data acquisition scheme used in Germany that is a result of several years of process development which helps to obtain as much detailed information as possible. Based on this an ideal database consists of five data set blocks [3]:

- Identification of the damage event: data, number;
- Information on the subsystem containing the faulty or damaged component: identifier, type of insulation, voltage level;
- Information on the damaged/faulty component: year of manufacturing, technology, manufacturer, installation year;
- Description of the damage/fault details: cause, occasion, maintenance measures, damage potential costs;
- Description of the network failure if relevant: condition, duration, affected clients, type of failure.

1.3 Criteria of proper dimensioning of LV cable

As it was mentioned in subchapter 1.2: during decades, there was observed a trend to neglect of storage of information regarding failures in LV networks especially exact reasons of failure. This fact means that people did not study well the situation and did not necessary measures to fix it. However, nowadays situation is changing and from Figure 1 it is possible to observe that the total length of LV grid is growing, and number of failures according to [3] number of failures due to cable failure decreased almost 4 times since 1983 to 2010 year. It means that the way in which people started to design and mount cables, new technologies that started to be used in manufacturing of cables, tests which allows to be aware of behavior of cable in different operation conditions are improving. Nevertheless, it is still necessary to realize that even with improvements of new technologies the human factor, e.g. design engineer of cables, is one of the most important.

Thus, for reliable design and dimension of LV cables it is recommended to consider following criterias:

1) Preparation of the documentation which is related to dimensioning of LV cables considering the National Standards of country for which calculations are made, for example:
   - IEC 60364-5-51:2005, *Electrical installations of buildings − Part 5-51: Selection and erection of electrical equipment – Common rules*;
   - IEC 60364-5-52:2001, *Electrical installations of buildings − Part 5-52: Selection and erection of electrical equipment – Wiring systems*;
   - IEC 60909-0:2016, *Short-circuit current calculation in three-phase a.c. systems – Part 0: Calculation of currents*;
   - IEC 60092-352:2005, *Electrical installations in ships – Part 352: Choice and installation of electrical cables.*
2) Collecting of input data which is necessary for proper dimensioning of the cable considering Standard according to which the calculation was decided to be made. In current thesis is considered IEC 60364-5-52 Standard as a main Standard for EU countries. Part 5-52 of IEC 60364 deals with the selection and erection of wiring systems for power and lighting or signaling and control purposes.
   - Definition of the earthing system type of LV network [6]:
     - TN-C system in which neutral and protective conductor functions are combined in a single conductor throughout the system;
     - TN-S system in which, throughout the system, a separate protective conductor is used;

- TN-C-S system in which neutral and protective conductor functions are combined in a single conductor in a part of the system;
- IT power system has all live parts isolated from earth or one point connected to earth through an impedance.;
- TT system has only one point directly earthed and the exposed-conductive-parts of the installation are connected to earth electrodes electrically independent of the earth electrode of the supply system.

- Performance of the following steps [7]:
  - Load analysis:
    a) definition of the power absorbed by the loads and relevant position;
    b) definition of the position of the power distribution centers (switchboards);
    c) definition of the paths and calculation of the length of the connection elements;
    d) definition of the total power absorbed, considering the utilization factors and demand factors.
  - Dimensioning of transformers and generators with margin connected to future predictable power supply requirements;

3) Dimensioning of conductors:
   - evaluation of the load current in the single connection elements;
   - definition of the conductor type (conductors and insulation materials, configuration);
   - definition of method of installation. The method of installation of a wiring system means the type of conductor or cable used, provided the correction factors due to the external influences are considered (described in Chapter 2);
   - definition of the cross-section and of the current carrying capacity;
   - voltage drop at the load current and under specific conditions (starting of a motor);
4) Performance of short-circuit current calculations maximum values;
5) Verification of a conductor for necessary conditions: withstand to short-circuit current, maximum temperature of the conductor in normal and due to short-circuit conditions, power losses and etc.
6) In case if one of the conditions from step 3 or 5 is unsatisfied it is necessary to check calculations from step 1, 2 and repeat step 3, 4 and 5.

By following above mentioned steps, it is possible to achieve a proper cable design, which will serve longer time with high reliability index even in abnormal situations. Consequences which could happen due to bad design are listed below:

1) Decreasing of a lifetime of the cable;
2) Overheating of cable which could cause a breakdown of insulation of the cable;
3) High power losses which are in square dependence of resistance of a cable and, therefore, to cross-section of cable. It causes increasing of temperature of the cable and higher spends for consumer;
4) High voltage drop which cause low quality of supplied electricity to end consumer and could cause burning of equipment;
5) Breakdown of the cable (Figure 5) which could cause high money spends due to repairing or changing and outage of the consumer;

Figure 5 – Breakdown of LV underground cable

6) Hazardous cases for people which could be lethal.

2 Impact of External Factors on Cable Sizing

In subchapter 1.3 was given a description of criteria of proper dimensioning of LV cable. In step 3 was mentioned that definition of the cross-section and of the current carrying capacity of a cable should be done considering correction factors. What is necessary to understand by "correction factor" exactly and how to consider it within calculations will be described in this chapter.

Correction factor means consideration of external factors which are different from reference values and could cause changes of the operation process of the cable and are considered within calculations of current carrying capacity of the cable.

The current-carrying capacity means the current to be carried by any conductor for sustained periods during normal operation shall be such that the temperature limit of the insulation (Table 3) is not exceeded. For some special cases and locations should be considered minimum temperature limits as well, as it could cause ageing of insulation and cause failure of cable.

Type of insulation	Temperature limit, °C
Thermoplastic (PVC)	70 at the conductor
Thermosetting (XLPE or EPR rubber)	90 at the conductor
Mineral 1 (thermoplastic (PVC) covered or bare exposed to touch)	70 at the sheath
Mineral 2 (bare not exposed to touch and not in contact with combustible material)	105 at the sheath
NOTE 1 For the temperature limit for other types of insulation, please refer to cable specification or manufacturer.	

Table 3 – Maximum operating temperatures for types of insulation

As it was mentioned before, all consideration in current Diploma Thesis are made mainly in accordance with IEC 60364-5-52 Standard. External factors should be considered during choosing of method of installation. According to IEC 60364-5-52 Standard there are several main reference methods by which are meant those methods of installation for which the current-carrying capacity has been determined by test or calculation and can be used safely and they are following (Table 4):

- **Reference methods A1** (insulated conductors in conduit in a thermally insulated wall) **and A2** (multi-core cable in conduit in a thermally insulated wall). The wall consists of an outer weatherproof skin, thermal insulation and an inner skin of wood or wood-like material.
- **Reference methods B1** (insulated conductors in conduit on a wooden wall) **and B2** (multi-core cable in conduit on a wooden wall). Conduit mounted on a wooden wall so that the gap between the conduit and the surface is less than 0,3 times the conduit diameter.
- **Reference method C** (single-core or multi-core cable on a wooden wall). Cable mounted on a wooden wall so that the gap between the cable and the surface is less than 0,3 times the cable diameter.
- **Reference method D1** (multi-core cable in ducts in the ground) **and D2** (multi-core cables designed to be buried directly in the ground). Cables drawn into 100 mm diameter plastic, earthenware or metallic ducts laid in direct contact with soil having a thermal resistivity of 2.5 K·m/W and a depth of 0,7 m.
- **Reference methods E, F and G** (single-core or multi-core cable in free air). A cable so supported that the total heat dissipation is not impeded. Heating due to solar radiation and other sources shall be considered.
-

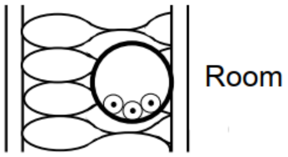
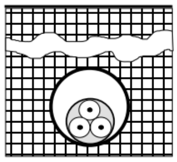
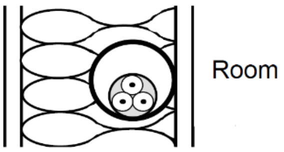
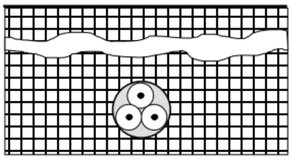
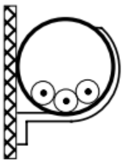
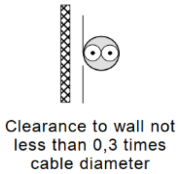
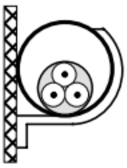
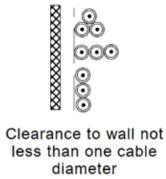
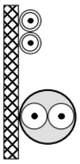
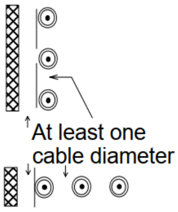
Reference method of installation					
A1		Insulated conductors (single-core cables) in conduit in a thermally insulated wall	D1		Multi-core cable in ducts in the ground
A2		Multi-core cable in conduit in a thermally insulated wall [1)]	D2		Sheathed single-core or multi-core cables direct in the ground.
B1		Insulated conductors (single-core cables) in conduit on a wooden wall	E		Multi-core cable in free air
B2		Multi-core cable in conduit on a wooden wall	F		Single-core cables, touching in free air
C		Single-core or multi-core cable on a wooden wall	G		Single-core cables, spaced in free air
1) In Standard 60364-5-52 is given wrong picture according to description.					

Table 4 – Basis reference methods

However, external factors which are listed in Table 4 do no affect on calculations and dimensioning of the cable but only on design of the wiring system itself. The external factors which are significant for calculations and dimensioning of the cable are described below.

2.1 Ambient temperature

According to [7], the reference ambient temperature for mediums where cables are located is different:

- for insulated conductors and cables in air: 30 °C;
- for buried cables in the ground: 20 °C.

Code	External influences
AA	Ambient temperature
-	External heat sources
AD or AB	Presence of water or high humidity
AE	Presence of solid foreign bodies
AF	Presence of corrosive or polluting substance
AG	Impact
AH	Vibration
AK	Presence of flora and/or mould growth
AK	Presence of fauna
AN	Solar radiation
AP	Seismic effects
AR	Wind
BE	Nature processed or stored materials
CB	Building design

Table 5 – Significant external influences for erection of the wiring system

Where the ambient temperature in the intended location of the insulated conductors or cables differs from the reference ambient temperature, the appropriate correction factor shall be applied to the values of current-carrying capacity.

The reason due to which is necessary to consider ambient temperature during dimensioning of the cable is that insulation of the cable is designed to withstand up to limit temperature during normal operation of the cable (Table 3). As ambient temperature could differ from nominal (reference) the final temperature of insulation of the cable could exceed limits what is prohibited. The temperature of the conductor could be presented by sum [8]

$$\theta = \theta_{amb} - \vartheta, \tag{1}$$

where θ_{amb} – ambient temperature, °C;

ϑ –difference between ambient temperature and temperature of the conductor, °C.

Heat transfer from the heated surface to external medium depends on difference of temperature in general. As limit temperature of the conductor is set, increasing of ambient temperature means decreasing of available difference of temperature. Thus, to save the balance of temperatures it is necessary to decrease load of the conductor [8].

Therefore, it is easier to change cross-section of the cable as produced heat by cable is proportional to cross-section of the cable according to equations (1) and (2) [8] than to apply methods for changing of ambient temperature.

$$P = I^2 \cdot R = \Phi, \tag{2}$$

$$R_n = \rho_0 \cdot \frac{l}{S}. \tag{3}$$

where P – active losses which occurs in the cable during normal operation, W;

R – active resistance of the cable at “cold” condition, Ohm

Φ – heat flux, W;

ρ_0 – the nominal resistivity of the cable core material, Ohm·mm^2 / m;

l – length of the cable, m;

S – cross-section of the cable, mm^2.

Not considering ambient temperature and applying correction factor along to calculation could decrease lifetime of the cable, could cause an overload of the cable, accelerate ageing of insulation of the cable what could cause breakdown of insulation and as a consequence failure and outage of the consumer. With increasing cross-section of the cable, the surface from which heat will dissipate will increase and, therefore, cooling will be faster. In Table 6 are shown effects which could be caused by thermal ageing factor [3].

Ageing factor	Ageing mechanism	Effects
• High temperature • Temperature cycling	• Chemical reaction • Incompatibility of materials • Thermal expansion • Diffusion • Anneal locked-in mechanical stresses • Melting/flow of insulation	• Hardening, Softening, loss of mechanical strength, embrittlement; • Increase tan delta; • Shrinkage, loss of adhesion, separation, delamination at interfaces; • Swelling; • Loss of liquids, gases; • Conductor penetration; • Rotation of cable; • Formation of soft spots, wrinkles; • Increase migration of components
• Low temperature	• Cracking • Thermal contraction	• Shrinkage, loss of adhesion, separation, delamination at interfaces; • Loss/ingress of liquids, gases; • Movement of joints, terminations.

Table 6 – Effects caused by ageing mechanisms due to exceeding temperature

According to [3], there is a strong and linear correlation between temperature rise and failures occurred due to cable failure. The Figure 6 and Figure 7 which are below represents a seasonal cable incident plot and average number of failures. There is an observable increase in the number of incidents in summer months that are associated to higher temperatures and generally drier weather (and soil).

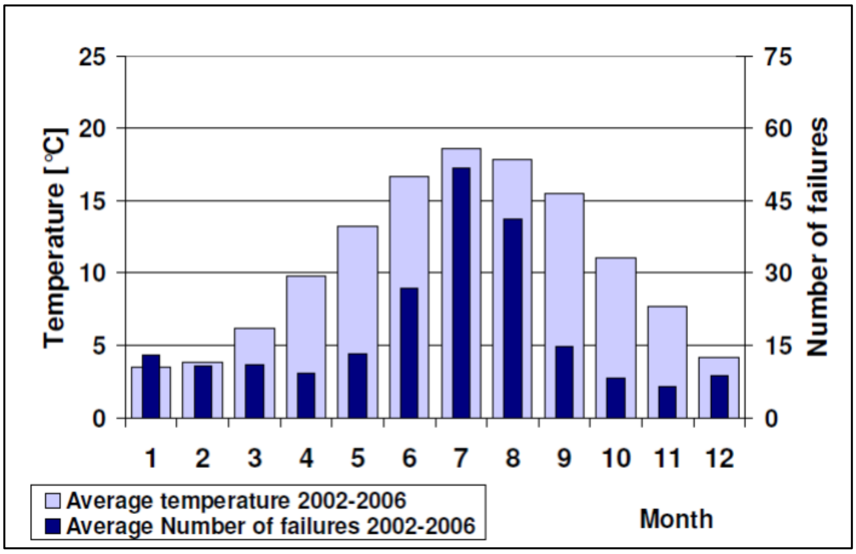


Figure 6 – Average ambient temperature per month and average number of failures

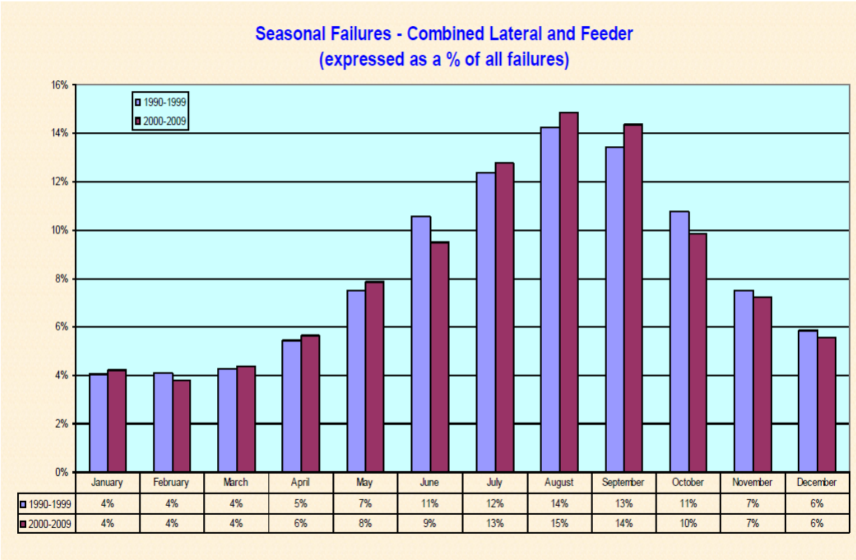


Figure 7 – Seasonal behavior of cable incidents

2.2 Laying method and number of circuits

Dissipated heat of the cable depends on its construction and laying method. If the cable is buried directly in the ground or in the ducts, heat transfer is caused by thermal conductivity of insulation, sheath, armor and soil. If the cable is laid in the air, heat transfer is caused by thermal resistivity of air. Heat from external surface of the cable to walls of conduit or tray is transferred by convection and radiation. It means, by choosing laying method needs to be considered heat transfer between the cable and ambient environment [8]. However, by choosing method of installation of the wiring system according to IEC 60364-5-52 reference environmental conditions were already considered by engineers during calculations and tests what makes selecting process much easier [6].

The cable current carrying capacity is influenced by the presence of other cables installed nearby. The heat dissipation of a single cable is different from that of the same cable when installed next to the other ones. If a number of cables is installed together and each is carrying the current, they will all warm up. Those which are on the outside of the group will be able to transmit heat outwards but will be restricted in losing heat inwards towards other warm cables. Because of this, cables installed in groups with others (for example, if enclosed in a conduit or trunking) are allowed to carry less current than similar cables clipped to, or lying on, a solid surface which can dissipate heat more easily [9]. The number of conductors to be considered in a circuit are those carrying load current. The total number of cables is taken as the number of circuits.

When talking about number of circuits and laying method, it is necessary to consider following definitions [7]:

- Layer: several circuits constituted by cables installed one next to another, spaced or not, arranged horizontally or vertically. The cables on a layer are installed on a wall, tray, ceiling, floor or on a cable ladder (Figure 8, a);
- Bunch: several circuits constituted by cables that are not spaced and are not installed in a layer; several layers superimposed on a single support (e.g. tray) are considered to be a bunch (Figure 8, b).

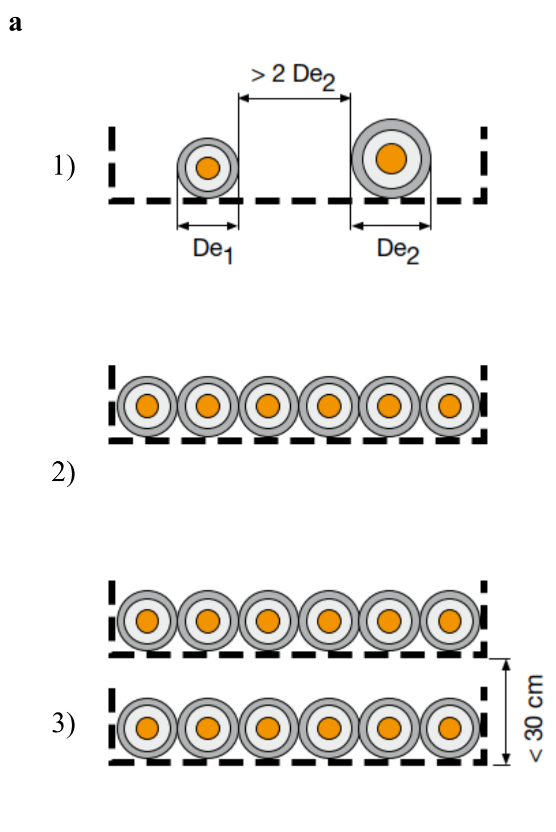


Figure 8 – Installation of cable
a – Cables in layer (1 – spaced; 2 – not spaced; 3 – double layer); b – Bunched cables (1 – in trunking, 2 – in conduit; 3 – on perforated tray)

The correction factors for bunched cables or cables in layers are calculated by assuming that the bunches consist of similar cables that are equally loaded. A group of cables is considered to consist of similar cables when the calculation of the current carrying capacity is based on the same maximum allowed operating temperature and when the cross-sections of the conductors is in the range of three adjacent standard cross-sections [6], [7].

Another factor which should be considered while choosing of laying method is a formation of cables and distance between the cables. According to IEC 60364-5-52 there are distinguished two main formations of cable which are widely used in three-phase systems:

- Trefoil formation (Figure 9, a);
- Flat formation (Figure 9, b).

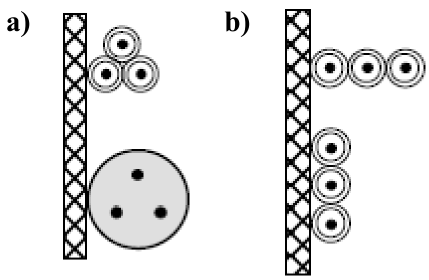


Figure 9 – Formation of cables
a) – trefoil formation; b) – flat formation

The choice between these two types of power cable placement depends on several factors like screen bonding method, conductor cross-sectional area and available space for installation [10].

In article [11] is presented a thermal analysis of the cables in free air according to which were made numerous finite-element method simulations (FEM) which were performed until the steady-state condition to validate IEC 60287-2-1 Standard [11].

For the calculation of the steady-state temperature of trefoil formation, the IEC [1] assumes that all cables have the same final temperature. Three equally loaded cables are assembled in a trefoil formation as shown in Figure 10. According to results of simulation for trefoil formation of cables it was stated that the hottest cable in the group is always the cable on top, while the IEC Standard assumes that all three cables have the same final temperature.

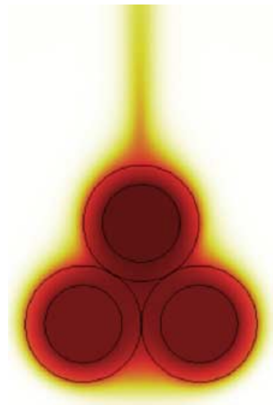


Figure 10 – Distribution of the steady temperature field for a trefoil formation (touching cables)

As for flay formation, first of all we need to distinguish two type of installation:

- Group of horizontal cables:

  Same assumption as for trefoil formation: the cables are equally loaded. For flat formation additional condition was considered: dependence of the final temperature on the distance between the cables – and presented three distinct regions:

  - Region 1 – When cables are touching or are very close to each other (maximum separation of around 0.1 of external diameter of the cable).
  - Region 2 – When cables are separated from each other, but the separation distance is not sufficient for the cables to be isolated from each other.
  - Region 3 – When cables are sufficiently far from each other and induced heating is negligible.

  Grouping cables affect the heat transfer because of induced heating. Whenever cables are touching, grouping plays a dominant role since contact prevents cables from transferring heat to the surrounding air. This behavior can be observed in Figure 11 (Region 1). In Region 2, cables are separated from each other and convection heat transfer takes place. In Region 3, the induced heating is negligible, and each cable can be assumed to be isolated [11].

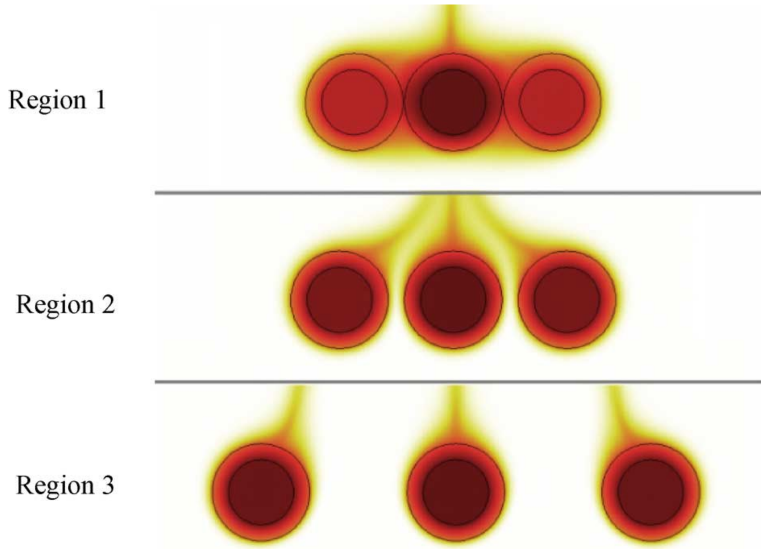


Figure 11 – Distribution of the steady temperature field for a group of horizontal cables, touching and not touching

- Group of vertical cables

  Same conditions for group of vertical cables were made as for group of horizontal cables but only orientation in space is different and, therefore, results as well.

  The results show that there are many similarities with the case with cables installed in the horizontal configuration [11]. The most important difference is that in the vertical configuration, heat convection from the cables below contributes more to the induced heating (Figure 12). In fact, because the cables are placed one on top of the other, the heat dissipated from the lower cables increases the temperature of the cables above. When the cables are touching, or very close to each other, the hottest cable is the one in the center of the group. When the separation distance increases, the hottest spot migrates to the cable on top, while in the horizontal grouping, the center cable is always the hottest [11].

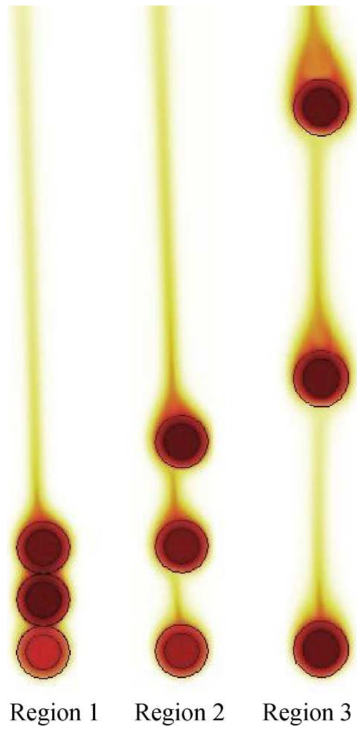


Figure 12 – Simulation of a group of vertical cables touching and not touching arrangements

From Figure 10, Figure 11 and Figure 12 could be observed that distance between the cables has crucial impact on the final temperature of the cables even it was modeled only for one circuit. It could be easily assumed that with increasing the number of circuits there will be more circuits which has higher temperature due to induced heating from other cables.

As effect of distance between the cables on final temperature of the cable is significant for reference methods D, E, F and G in IEC 60364-5-52 Standard are given additional correction factors which shall be considered during dimensioning of the cable:

- for reference Method D – cable to cable clearance;
- for reference methods E, F, G – formation (trefoil, flat), orientation in space (horizontal, vertical), distance between cable (touching, not touching, spaced).

For buried cables in the ground (Reference method D) could be observed the same situation: dependence of final temperature of the cable on a distance between the cables or ducts. In addition to cable to cable clearance for buried cables in the ground there is strong dependency between depth of burying of cables and heat dissipation as the deeper cables are buried the more stable thermal environment. According to [4], correction factors given to cable to cable clearance for buried in the ground cables apply to an installation depth of 0.7 m and are applicable only for depth up to 0.8 m.

To sum up, during calculations of proper dimensioning of the cable corresponding correction factors due to number of circuits, formation of cables, orientation in space for current carrying capacity of the cable should be obtained to achieve the reliable performance of the cable during normal operation.

2.4 Soil thermal resistivity

Knowledge of soil physics is becoming critical in the design and implementation of underground power transmission and distribution systems. The reason is simple, and it was described above: electricity flowing in a conductor generates heat, a resistance to heat flow between the cable and the ambient environment causes the cable temperature to rise [12]. Since underground power cables operate at the maximum possible conductor current, heat dissipation from the conductor to the surrounding soil plays a crucial role in evaluating the performance of buried cable systems. The current-carrying capacity mostly depends on the conductor temperature: when it is too high, the cable can overheat [10].

Since the soil is in the heat flow path between the cable and the ambient environment, and therefore forms part of the thermal resistance, soil thermal properties are an important part of the overall design [12].

The traditional method used for calculating of the thermal resistance between the cable system and the external environment assumes that the soil is homogeneous with constant thermal conductivity. In fact, the soil is multilayered and consists of organic matter, sand, clay, gravel and other materials. Heat conduction from the hot cable to the external environment depends on the thermal conductivity of each layer, which, in turn, depends on the porosity, liquid-vapor transport, and temperature [10]. When the pores are saturated with water, the thermal conductivity of the soil increases. On the other hand, the thermal conductivity of the soil layers decreases with temperature [10]. Moreover, the shape of the trench, cable location, and configuration of the soil layers influence the temperature distribution in the soil and cable.

According to [4], current carrying capacities for buried in the ground cables were calculated for soil thermal resistivity of 2.5 K·m/W as a precaution for worldwide use when the soil type and geographical location are not specified.

Values of soil thermal resistivities for which correction factors are given according to IEC 60364-5-52 Standard are presented in Table 7.

Soil thermal resistivity, K·m/W	Description
0.5, 0.7	Very moist soil (saturated)
1, 1.5	Wet soil
2	Damp soil
2.5	Dry soil (reference)
3	Very dry soil

Table 7 – Specified values of soil thermal resistivities

In article [12] is presented a thermal analysis of HV underground transmission line. Even if it is HV cables physical processes which occurs are almost similar for all levels of voltages with negligible differences.

We consider the in-line arrangement of the cables buried in the multilayered soil (the native soil and the thermal backfill). The shape of the backfill bedding, presented in this study, differs from those analyzed in the literature. The burial depth of the cables measured from the reference level (0.5 m below the ground) varies from 2 to 6 m [12].

The numerical simulations performed in this paper consider three different conditions of cable placement:

<u>Case 1.</u> The cables are located in the high-density polyethylene (HDPE) casing pipes, filled with sand-bentonite mixture (SBM), and located in the fluidized thermal backfill (FTB) bedding, buried in the native soil (Figure 13, a);

<u>Case 2.</u> The power cable installation in the HDPE casing pipes (filled with SBM) buried in the native soil (Figure 13, b)

<u>Case 3.</u> The cable laying in HDPE casing pipes filled with dry sand. The HDPE casing pipes are buried in the native soil (Figure 13, c)

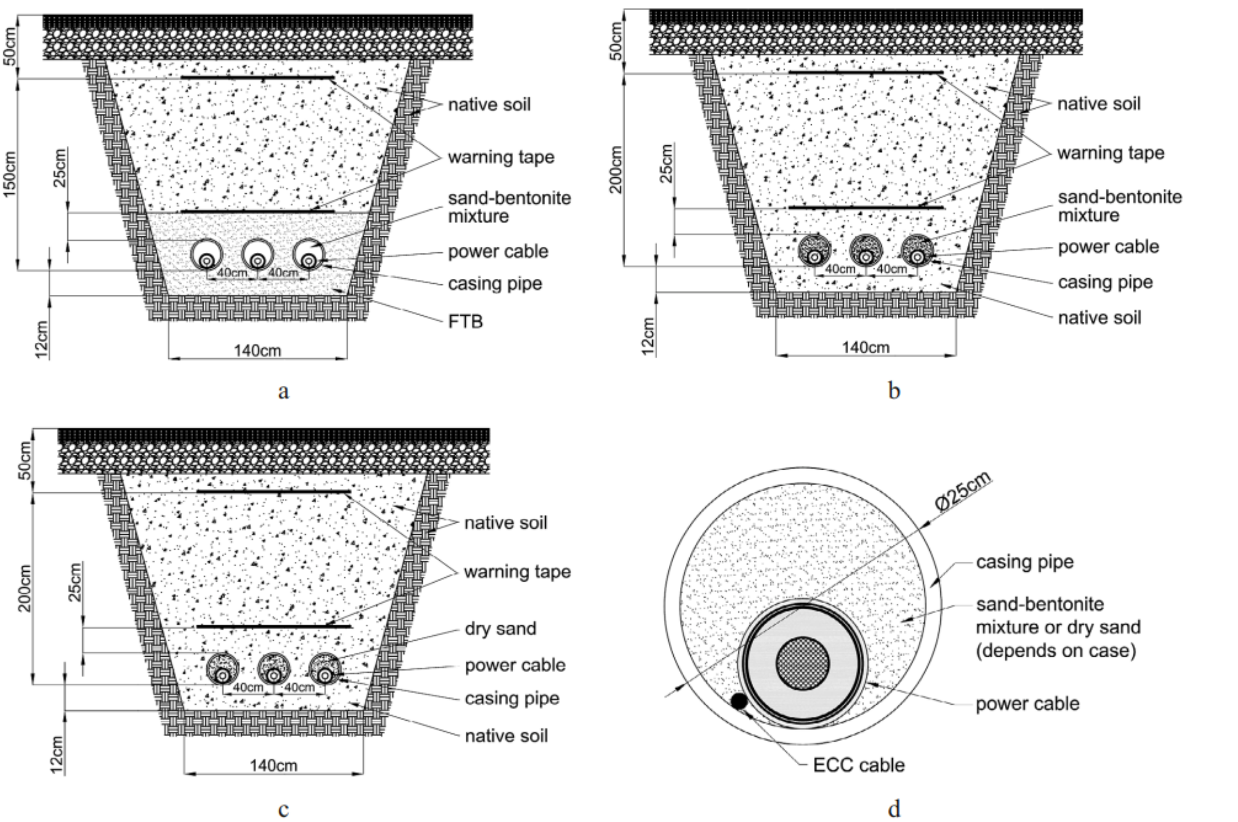


Figure 13 – The power cable laying conditions
a – case 1; b – case 2; c – case 3; d – cross-section of power cable

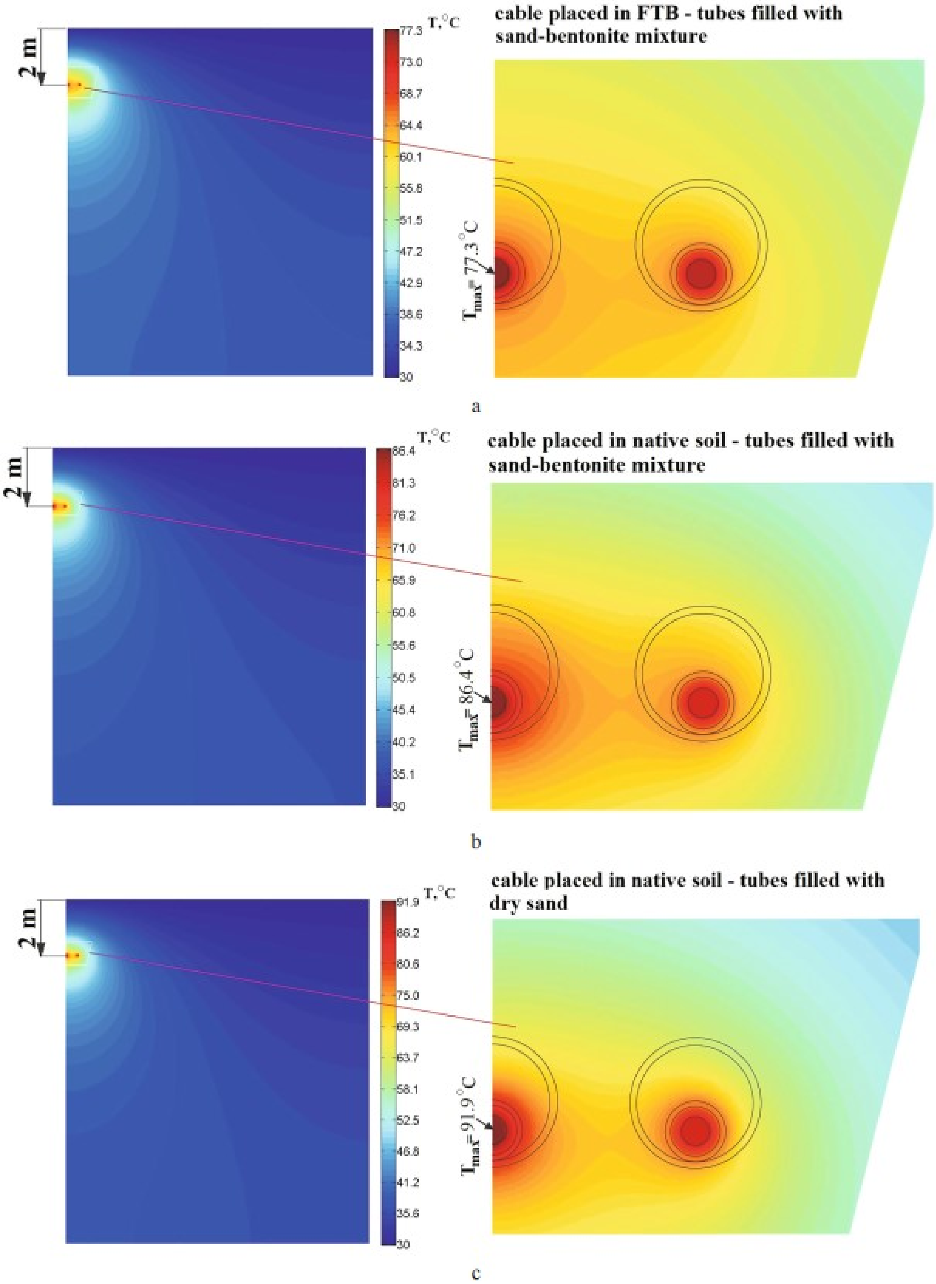


Figure 14 – Temperature distributions obtained for the layout conditions of the power cable shown in Figure 13 and burial depth of 2 m

Figure 14 presents the temperature distributions obtained for cable burial depth of 2 m. The lowest value of the maximum cable temperature 77.3 °C is obtained in the case 1 (Figure 14, a). Then, the largest temperature of the conductor 91.9 °C is obtained in case 3 (Figure 14, c). It should be noted that the maximum allowable temperature 90°C according to IEC 60364-5-5 Standard is exceeded in that case. The maximum temperature of the cable core is 86.4 °C in case 2 [10].

Based on calculations of the steady-state temperature of buried in the ground cables for different depths within range of 2 m up to 6 m [10], there were presented results which reflect the dependence of final temperature of the cable on depth of burry (as it was mentioned in subchapter 2.4). The calculated maximum temperature of the conductors located at different burial depths is presented in Figure 15. According to the mentioned results, it could be obtained that for case 1 as it was mentioned with 2 m depth the final temperature is 77.3 °C and for the burial depth 6 m the temperature is 143.6 °C.

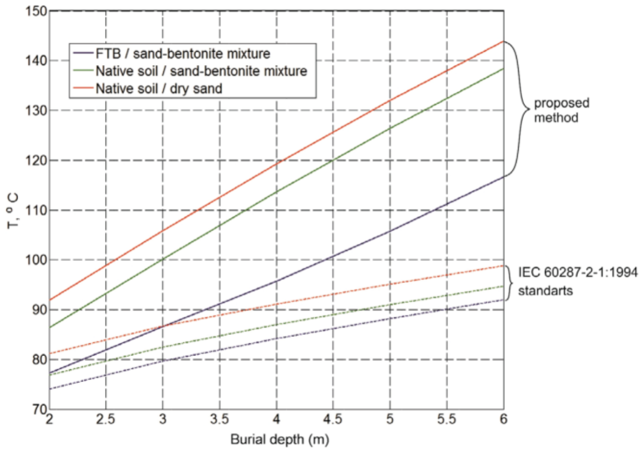


Figure 15 – The calculated maximum temperature of the conductors located at different burial depths [10]

To sum up, there is a high dependency of final temperature of the cable on burying depth of the cable and soil thermal conductivity which should be considered as a correction factor to current carrying capacity of the cable while dimensioning of cable to achieve proper performance of the cable during normal operation and not to obtain its overheating.

2.5 Mechanical stresses

According to [6], due to mechanical reasons as an external influence should be considered not a correction factor but minimum cross-section of a conductor to provide sufficient mechanical protection. The minimum cross-sections of conductors for fixed installations due to mechanical reasons are presented in Table 8.

Type of wiring system	**Use of the circuit**	**Conductor**	
		Material	**Cross-section, mm^2**
Cables and insulated conductors	Power and lighting circuits	Copper	1.5
		Aluminium	10
	Signaling and control circuits	Copper	0.5
Bare conductors	Power circuits	Copper	10
		Aluminium	16
	Signaling and control circuits	Copper	4

Table 8 – Minimum cross-section of conductors

For connections with flexible insulated conductors and cable could be used cables which minimum cross-section is 0.75 mm^2.

2.6 Conclusion regarding external factors

From abovementioned subchapters (subchapters 2.1 – 2.5) it is necessary to say that the main impact from external factors and which are considered as correction factors is temperature aspect. Each of mentioned external factors cause changing of final temperature of the conductor and as the result could cause overheating of it. So, it is necessary to consider correction factor which will decrease current carrying capacity and will cause increasing of cross-section of the conductor.

3 Algorithm Creation for Cable Sizing According to IEC 60364-5-52 and its Implementation in Chosen Software Tool

3.1 Description of dimensioning of the cable

As it was mentioned in subchapter 1.3: part 5-52 of IEC 60364 Standard deals with the selection and erection of wiring systems for power and lighting or signaling and control purposes. Unfortunately, in the standard itself not mentioned a procedure and calculations which should be done during dimensioning of the cable. However, all necessary recommendations which should be considered for proper dimensioning are given. Some of these recommendations were described in chapter 2 and will be described during the current chapter.

On the Internet and in studying materials there are lots of algorithms for proper dimensioning of the cable according to the IEC 60364-5-52 Standard. However, for further developing of the own algorithm it was taken only one among of them as the core: ABB Electrical installation handbook: Protection, control and electrical devices. Technical guide - 6th edition 2010 – as one of the most reliable sources. The algorithm was developed focused on the recommendations and rules of IEC 60364-5-52 Standard in general. If something in Electrical installation handbook was not in accordance with the standard, priority was given to the standard then.

In the subchapter 1.3 during description of criteria for proper dimensioning of LV cable it was mentioned that before sizing of cable it is necessary to perform certain steps: load analysis and dimensioning of transformers and generators. As soon as it was done, it is possible to prepare necessary input data for further dimensioning of the cable.

First of all, it is mandatory to distinguish input data for two main parts:

- Load input data. Such inputs data usually comes from load analysis or is directly given by customer and is validated by the engineer then;
- Cable input data. Such data should be chosen and validated by engineer or directly given by customer and is validated by the engineer then.

In general, the IEC 60364-5-52 Standard allows to dimension the cable only according to the nominal current carrying capacity and certain external influences, and a voltage drop (chapter 2). However, during dimensioning of the cable there are much more conditions which should be considered for proper design (subchapter 3.4). Due to that fact the above-mentioned reason usually for regular erection of the cable according to IEC 60364-5-52 Standard the list of necessary input data is less than for verification of additional conditions and it will be described below. Additional data will be described in subchapter 3.4.

3.1.1 Load input data.

- Rated voltage (*U*). The value of the rated (nominal) voltage for calculated feeder/installation. It should be given in accordance with IEC 60038:2009 Standard;
- Number of phases. Determination either one-phase or three-phase system;
- Load current (I_b). The RMS. value of the current flowing through a line terminal of a winding when the rated voltage is applied at the rated frequency. It could be obtained from load analysis directly or to be calculated by means of other electrical parameters (rated voltage, number of phases, installed power and power factor). It is the main parameter according to which dimensioning of the cable is done;
- Power factor ($cos\varphi$). Defined as a ratio of the real power absorbed by the load to the apparent power flowing in the circuit. Needed for calculation of the load current (if necessary) and the voltage drop. Should be in range from 0 to 1. In case if value is not given should be assumed as average for calculated type of feeder;

- Installed power (P). The active power is the real power consumed by the load. It is not a required value as the load current is given usually as an input data. However, in some cases load current is not presented as an input. So, installed power could be used for calculation of the load current considering parameters mentioned above. In case of motors this value should be taken already considering efficiency and duty factor

3.1.2 Cable input data.

Before preparing cable input data it is recommended to set method of installation of the wiring system (see chapter 2). Recommendations depend on which method of installation shall be chosen according to [6] are shown in Table 9.

Situations		**Method of installation**							
		Without fixings	**Clipped direct**	**Conduit systems**	**Cable trunking (including skirting trunking, flush floor trunking)**	**Cable ducting systems**	**Cable ladder, cable tray, cable brackets**	**On insulator**	**Support wire**
Building voids	Accessible	40	33	41, 42	6,7,8,9,12	43, 44	30, 31, 32, 33, 34	-	0
	Not accessible	40	0	41, 42	0	43	0	0	0
Cable channel		56	56	54, 55	0		30, 31, 32, 34	-	-
Buried in ground		72, 73	0	70, 71	-	70, 71	0	-	-
Embedded in structure		57, 58	3	1, 2, 59, 60	50, 51, 52, 53	46, 45	0	-	-
Surface mounted		-	20, 21, 22, 23, 33	4, 5	6, 7, 8, 9, 12	6, 7, 8, 9	30, 31, 32, 34	36	-
Overhead/free in air		-	33	0	10, 11	10, 11	30, 31, 32, 34	36	35
Window frames		16	0	16	0	0	0	-	-
Architrave		15	0	15	0	0	0	-	-
Immersed		+	+	+	-	+	0	-	-
- Not permitted 0 Not applicable or not normally used in practice + Follow manufacturer's instructions									
NOTE The number in each box, e.g. 43, 44, refers to the number of the method of installation in Annex A									

Table 9 – Erection of wiring systems

Depending on chosen method of installation and reference method the will be a difference in input data. After reference method was set, procedure of dimensioning of cable could be continued:

1) Definition of main material parameters of the cable:

   1.1) Conductor material. As a conductor material it is recommended to use copper or aluminium. The choice depends on cost dimension and weight requirements, resistance to corrosive environments (chemical reagents or oxidizing elements). In general, the carrying capacity of a copper conductor is about 30% greater than the carrying capacity of an aluminium conductor of the same cross section. An aluminium conductor of the same cross-section has an electrical resistance about 60% higher and a weight half to one third lower than a copper conductor [7]. For the LV wiring systems copper conductors are met more often than aluminium. Aluminium is often used for cable sizing for older installations.

1.2) Insulation type. Insulation material (none, PVC, XLPE-EPR): the insulation material affects the maximum temperature under normal (see Table 3) and short-circuit conditions (see subchapter 3.4) and therefore the exploitation of the conductor cross-section. In case of mineral insulation in [6] current-carrying capacities are specified only for 500 and 750 V;

1.3) The type of conductor (bare conductor, single-core cable without sheath, single-core cable with sheath, multi-core cable) is selected according to mechanical resistance, degree of insulation and difficulty of installation (bends, joints along the route, barriers...) required by the method of installation and depends on earthing system as well [6]. Upon the choice there is a difference in current-carrying capacity of the cable. Some methods of installation are distinguished by different types of cables, for example, A1 and A2, B1 and B2. For choosing of type of the conductor it could be considered Table 10 according to [6].

Situations		**Method of installation**							
		Without fixings	**Clipped direct**	**Conduit systems**	**Cable trunking (including skirting trunking, flush floor trunking)**	**Cable ducting systems**	**Cable ladder, cable tray, cable brackets**	**On insulator**	**Support wire**
Bare conductors		-	-	-	-	-	-	+	-
Insulated conductors		-	-	+	+	+	-	+	-
Building voids	Accessible	+	+	+	+	+	+	0	+
	Not accessible	0	+	+	+	+	+	0	+
- Not permitted 0 Not applicable or not normally used in practice + Follow manufacturer's instructions									

Table 10 – Method of installation in relation to conductors and cables

2) Definition and clarification of arrangement:

2.1) Arrangement. Specification of the position (see names of columns in Table 9) and orientation of the wiring system in the space due to some methods of installation have several options. If chosen method of installation is referred to Reference method C, E, F and designed wiring system is three-phase it is necessary to determine formation of the cables as well (see subchapter 2.2);

2.2) Number of circuits or multi-core cables. The number of conductors to be considered in a circuit are those carrying load current. The total number of cables is taken as the number of circuits. If a circuit consists of *m* parallel conductors per phase this circuit should be considered as *m* circuits. If a group consists of *n* single-core cables it may either be considered as *n/2* circuits of two loaded conductors or *n/3* circuits of three loaded conductors [6].

2.3) Number of trays or ladders and number of circuits or multi-core cables per tray. Due to the particular arrangement of cables it is necessary to indicate number of trays and number of circuits per tray to apply proper correction factor to current carrying capacity and to obtain the total number of parallel runs in case of layer arrangement of cables.

2.4) Number of parallel runs. The total number of cables of the same size, length and which are equally loaded and usually supplying one feeder (number of parallel runs per phase). Always shall be considered within calculations connected with current;

2.5) Duct to duct (cable to cable) clearance. The value means distance between buried cables in the ground (either in ducts or directly in the soil) within Reference Method D and impact on current-carrying capacity of the cables (see subchapters 2.3, 2.4).

3) Definition of external parameters:

3.1) Ambient temperature (T). The ambient temperature is the temperature of the surrounding medium when the cables or insulated conductors under consideration are not loaded. As it was mentioned in subchapter 2.1: the reference ambient temperature for the insulated conductors and cables in air is 30°C; for buried cables in the ground (either in ducts or directly in the soil) is 20°C;

3.2) Soil thermal resistivity. The effective thermal resistance of the soil may affect the heat transfer process between the buried cables or ducts and the surrounding soil. The current-carrying capacities for cables in the ground relate to a soil thermal resistivity of 2,5 K·m/W (see subchapter 2.4);

3.3) Use of the circuit. The minimum cross-section of the cable due to mechanical reasons is predetermined by purpose of usage of the circuit according to IEC 60364-5-52 Standard (see subchapter 2.5);

4) Definition of voltage drop related parameters:

4.1) Length of the cable (L). The length of the wiring system from the connection point.

4.2) Permitted total voltage drop (ΔU_m). The voltage drop between the origin of an installation and any load point should not be greater than the values in Table 10 expressed with respect to the value of the nominal voltage of the installation.

Type of installation	Lighting, %	Other uses, %
Low voltage installations supplied directly from a public low voltage distribution system	3	5
Low voltage installation supplied from private LV supply	6	8
NOTE 1 When the length of cables of the installations is longer than 100 m, voltage drops which are mentioned in table 2 may be increased by 0,005 % per meter of wiring system. NOTE 2 A greater voltage drop may be accepted for motor during starting periods (point 4.3) or for equipment with high inrush current. Such values of the voltage drop should be taken in accordance with limits specified in the relevant equipment standard.		

Table 10 – Permitted voltage drop

4.3) Starting voltage drop threshold (ΔU_{Sm}). For motor feeders it is necessary to verify a voltage drop across the cable during starting of the motor in order not to cause disturbances in power network. If the starting voltage drop threshold is not specified by manufacturer, it is recommended to consider in range from 5 to 17% depends on power of the motor.

Starting current of a motor can be 5 to 7 times its full-load value (or even higher). If an 8 % voltage drop occurs at full-load current, then a drop of 40 % or more will occur during start-up. In such conditions the motor will either:

- Stall (i.e. remain stationary due to insufficient torque to overcome the load torque) with consequent over-heating and eventual trip-out;
- Accelerate very slowly, so that the heavy current loading (with possibly undesirable low-voltage effects on other equipment) will continue beyond the normal start-up period.

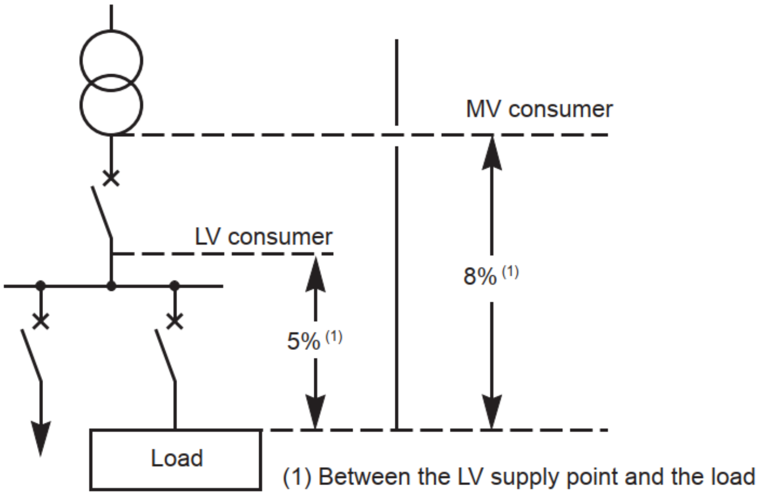


Figure 16 – Maximum voltage drop

4.4) Transformer incomer voltage drop (ΔU_T). The value represents voltage drop between secondary side of the step-down transformer and connection point of the calculated cable (main LV switchboard). The total allowed voltage drop is equal to summation of the transformer incomer voltage drop and voltage drop within the calculated cable.

5) Special parameter:

Third harmonic content.

Where the neutral conductor carries a current without a corresponding reduction in the load of the phase conductors, the current flowing in the neutral conductor shall be considered in ascertaining the current-carrying capacity of the circuit.

This neutral current is due to the phase currents having a harmonic content which does not cancel in the neutral (see Figure 17). The most significant harmonic which does not cancel in the neutral is usually the third harmonic. The magnitude of the neutral current due to the third harmonic may exceed the magnitude of the power frequency phase current. In such a case the neutral current will have a significant effect on the current-carrying capacity of the cables in the circuit.

Equipment likely to cause significant harmonic currents are, for example, fluorescent lighting banks and dc power supplies such as those found in computers.

The corresponding correction factors only apply in the balanced three-phase circuits (the current in the fourth conductor is due to harmonics only) to cables where the neutral conductor is within a four-core or five-core cable and is of the same material and cross-sectional area as the phase conductors.

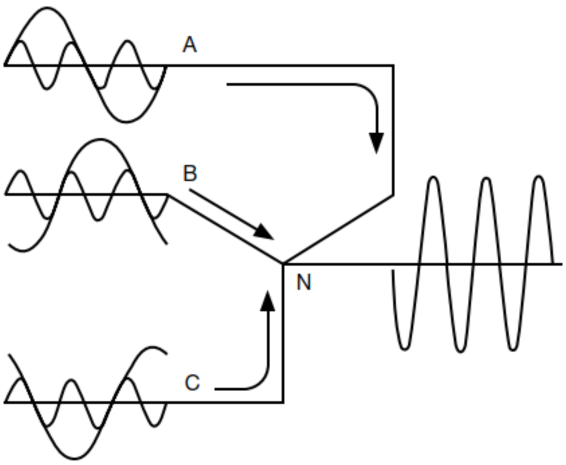


Figure 17 – Third harmonic current in neutral conductor

3.2 Theoretical algorithm for dimensioning of the cable

As basic description of necessary input data was given in previous chapter, algorithm for proper dimensioning of the cable should be specified next:

1) Performing of load flow analysis and dimensioning of transformers and generators;
2) Selection of wiring system (Table 10) and erection of wiring system (Table 9);
3) Choosing of a method of the installation (Annex A);
4) Calculation of the load current I_b, A, by means of the formula (4) or obtaining it directly from the customer:

$$I_b = \frac{P_n}{a \cdot n \cdot U_n \cdot cos\varphi}, \tag{4}$$

where P_n – the nominal active power of the normal load or rated power in case of the motor, W;

a – a coefficient which is equal $\sqrt{3}$ in case of three-phase system and 1 in case of one-phase;

n – the number of parallel runs per phase;

U_n – the value of rated (nominal) voltage for calculated feeder/installation, V;

$cos\varphi$ – the power factor.

5) Definition of cable related parameters depends on needs and restrictions:
   a. Definition of material of the core: Al/Cu;
   b. Definition of insulation material: none (bare), PVC, EXLP/EPR or other (in case of other insulation type than listed in Table 3, parameters of insulation should be specified with manufacturer);
   c. Definition of number of cores: single-core, multi-core, from 1 up to 5.
   d. Definition of the arrangement related parameters (see subchapter 3.1.2 part 2)
6) Definition of parameters related to correction factors:

6.1) Reference Method differ from D:

   a. Definition of the ambient temperature. Correction factor if temperature of the air is other than 30 °C k_1 could be obtained from the Table B.52.14 [6].
   b. Clarification of arrangement of cable. Correction factor for cables installed bunched or in layers or for cables installed in a layer on several supports k_2. If reference method is other that E, F, G than value should be obtained from Table B.52.17 [4]. For reference method E should be used Table B.52.20 [6] and for the rest B.52.21 [4].

6.2) Reference Method D:

   a. Definition of the ambient temperature. Correction factor if temperature of the ground is other than 20 °C k_1 could be obtained from the Table B.52.15 [6].
   b. Definition of cable to cable (duct to duct) clearance. Based on choice of reference method (D1 – single or multi-core cable in ducts in the ground; D2 – single or multi-core cables designed to be buried directly in the ground) there is a difference in correction factors due to clearance k_2: D1 – Table B.52.19 [6], D2 – Table B.52.18 [6].
   c. Definition of the soil thermal resistivity. Correction factors for soil thermal resistivities k_3 other than 2,5 K·m/W are given in Table B.52.16 [6].

6.3) Third harmonic content. In case if third harmonic content is presented and in range from 0 up to 33 size selection of the cable should be done based on line current, otherwise based on neutral current. If size selection is made based on neutral current designed (load) current should be recalculated by following formula:

$$I`_b = 3 \cdot k_{3h} \cdot I_b, \tag{5}$$

where k_{3h} - third harmonic content p.u.

Otherwise load current is equal to line current $I`_b = I_b$.

Reduction factor shall be chosen based on third harmonic content and Table E.52.1 [4].

7) Calculation of total correction factor k_{tot} which should be applied to current-carrying capacity of the cable:

$$k_{tot} = k_1 \cdot k_2 \cdot k_3 \cdot k_4, \tag{6}$$

where k_1 – a correction factor if temperature of the air or ground is other than reference one (depends on method of installation);

k_2 – a correction factor due to specific arrangement and number of circuits (depends on method of installation);

k_3 – a correction factor for soil thermal resistivities other than 2,5 K·m/W (applicable only for Reference Method D);

k_4 – a correction factor due to third harmonic content (depends on method of installation);

8) Calculation of current carrying capacity considering correction factors:

$$I`_0 = k_{tot} \cdot I_0, \tag{7}$$

where I_0 – reference current carrying capacity related to method of installation according to [6].

9) Determination of suitable cross-section of the cable S, mm^2, according to lowered current-carrying capacity by means of following equation:

$$I`_0 > I_b, \tag{8}$$

where I_b – load current, A. In case of presenting of third harmonic content recalculated $I`_b$ current shall be used.

The way how to apply equation (7) is following:

Based on load current it is necessary to find such current carrying capacity of cable within Tables B.52.2 – B.52.13 [6] considering of chosen method of installation and apply total correction factor to it. After it is done, compare obtained value with load current, if it satisfies condition (7) then cross-section was chosen properly by the first view. If no, choose higher value of current-carrying capacity and therefore of cross-section of the cable.

10) Definition of parameters related to calculation of voltage drop:
    a. Specification of length of the cable;
    b. Definition of threshold voltage drops: permitted total voltage drop, maximum voltage drop during starting of motor (if relevant), transformer incomer voltage drop;

11) Calculation of voltage drop across the cable during normal operation ΔU_c, V, [6]:

$$\Delta U_c = b \cdot l \cdot \left(\frac{\rho_1}{S} \cdot cos\varphi + \lambda \cdot sin\varphi\right) \cdot I_b, \tag{9}$$

$$\rho_1 = \rho_0 \cdot (1 + \alpha \cdot \theta), \tag{10}$$

where b – the coefficient equal to 1 for three-phases circuits, and equal to 2 for single-phase circuits [6];

ρ_1 – the resistivity of conductors in normal service, taken equal to the resistivity at the temperature in normal service [6], Ohm·mm^2/m;

α – the temperature coefficient of resistivity for conductor material, (°C)$^{-1}$.

λ – the reactance per unit length of conductors, which is taken to be 0,08 mOhm/m in the absence of other details [6].

12) Calculation of total voltage drop from secondary LV side of step-down transformer up to end feeder:

$$\Delta U = \Delta U_c + \Delta U_t, \tag{11}$$

where ΔU_t – the transformer incomer voltage drop, V.

Voltage drop could be found as p.u. value by following equation [6]:

$$\Delta u = \frac{\Delta U}{U_0}, \tag{12}$$

where U_0 – the phase-to-ground voltage, V.

13) Verification of voltage drop according to following equation:

$$\Delta u_{max} > \Delta u, \tag{13}$$

where Δu_{max} – maximum permitted voltage drop according to [6] (see Table 10).

14)* In case of motor load type, it is necessary to check voltage drop during start-up of motor. It could be recalculated considering voltage drop during normal operation and ratio of the start-up current to the nominal current of the motor. Ratio should be specified by manufacturer or assumed. According to [13], for LV motors ratio between start-up and rated currents is 5 and it could be taken.

$$\Delta U_m = \frac{I_{sb}}{I_b} \cdot \Delta U, \tag{14}$$

where $\frac{I_{sb}}{I_b}$ – the ratio of the start-up current to the nominal current of the motor. Equal to 5 according to [13] in case of not specified value by manufacturer.

After recalculation of voltage drop, condition (12) should be verified again. However, instead of value from Table 10 should be taken another limited value. It could be specified by manufacturer in equipment manual or assumed by engineer. According to working practice of ABB engineers, the range in which voltage drop during start-up of motor is from 5 to 17 percent and depends on purpose of usage of motor, its electrical size and level of voltage.

3.3 Extra conditions to be checked during dimensioning of the cables

In previous chapter algorithm for dimensioning of the cable according to current currying capacity [6] was given. However, in practice such dimensioning is not sufficient and there are several more conditions which shall be considered within designing:

1) Joele losses. Mentioned losses are caused by flowing of current across the cable and its resistance. The lost energy is dissipated in heat and could cause extra heating of the conductor and the ambient medium. Joule losses could be derived by following equation:

$$\Delta P = \frac{c \cdot R_1 \cdot I_b^2}{1000}, \tag{15}$$

where *c* – the coefficient which is equal 2 for one-phase circuits and 3 for three-phase;

R_1 – resistance of the cable which is calculated with resistivity ρ_1 according to (3).

Joule losses usually considered in case if economical aspect within dimensioning of the cable is considered. It means that with increasing of cross-section of the cable joule losses are lower (see equation (14). On the other hand, cost of the conductor is higher due to higher amount of metal is needed.

Verification for Joule losses is obligatory condition which is usually checked only by request.

2) Short-circuit current withstand. According to [14] for LV installations with fault clearing time not exceeding 5 s the time *t*, in which highest permissible temperature of insulation of the cable in normal operation will reach the maximum permissible temperature due to short-circuit could be obtained by following equation:

$$t = (k \cdot S/I)^2, \tag{16}$$

where S – the cross-section of the cable, mm^2;

I – the prospective initial short-circuit current, A;

k – a factor taking account of the resistivity, temperature coefficient and heat capacity of the conductor material, and the appropriate initial and final temperatures. It differs depend on insulation and core types and could be calculated using following equation [15]:

$$k = \sqrt{\frac{Q_c \cdot (\beta + 20)}{\rho_{20}} \cdot \ln\left(\frac{\beta + \theta_f}{\beta + \theta_i}\right)}, \tag{17}$$

where Q_c – is the volumetric heat capacity of conductor material at 20 °C, J/K·mm^3;

β – is the reciprocal of temperature coefficient of resistivity at 0 °C for the conductor, °C;

ρ_{20} – is the electrical resistivity of conductor material at 20 °C, Ω·mm;

θ_f – final temperature of the conductor, °C;

θ_i – initial temperature of the conductor, °C.

Value $\sqrt{\frac{Q_c \cdot (\beta+20)}{\rho_{20}}}$ could be replaced by *K* letter for simplification.

From abovementioned equation could be derived a condition which is mandatory to be checked during dimensioning of the cable:

$$I^2 \cdot t \leq k^2 \cdot S^2, \tag{18}$$

where $I^2 \cdot t$ – let through energy of Joule thermal integral, A^2·s. This value usually is given by manufacturer in equipment manual to protective device or could be calculated manually from passport values. In case if such value is not specified at all, could be used for calculations prospective initial short-circuit current and assumed fault clearing time which is usually in range of from 0.1 to 1 s at maximum.

In some cases, short-circuit withstand current within certain time (usually 1 s) of the cable is given by manufacturer and could be recalculated to fault clearing time by following equation:

$$I_t = \frac{I_{scn}}{\sqrt{t}}, \tag{19}$$

where I_t – withstand short-circuit current for *t* s, A;

I_{scn} – nominal withstand short-circuit current for 1 s, A.

After recalculation of current simplified equation for verification of short-circuit current withstand could be used according to [13]:

$$I_{th} \leq I_{thc}, \tag{20}$$

where I_{th} - the thermal equivalent short-circuit current, A. It is calculated according to (17) and used values are prospective initial short-circuit current and clearing time.

I_{thc} - withstand short-circuit current for t s, which is given by manufacturer, A.

According to practice experience of ABB engineers and analysis of short-circuit studies, thermal equivalent short-circuit current which is obtained from short-circuit current calculations in most cases is equal to initial short-circuit current. Due to that reason, it is possible to assume following equation by rewriting (18):

$$I``_k \leq I_{thc}. \tag{21}$$

Besides checking of the cable for let-through energy, additional checking of the cable for final-state temperature due to short-circuit current could be applied as well. First of all, it is important to evaluate temperature of the cable during normal operation right before short-circuit occurs considering ambient temperature, load current and nominal current of the cable based on following equation [8]:

$$\theta_i = \theta_{amb} + (\theta_{nom} - \theta_{amb.nom}) \cdot \left(\frac{I_b}{I`_0}\right)^2, \tag{22}$$

where θ_i – initial temperature of the cable right before short-circuit occurs, °C;

θ_{nom} – nominal temperature of the cable, °C. Usually provided by manufacturer but for worse conditions could be used maximum allowable temperature (Table 3);

$\theta_{amb.nom}$ – reference ambient temperature of the media (mentioned in the beginning of the subchapter 2.1), °C.

After initial temperature was evaluated it is possible to estimate final-state temperature due to short-circuit current based on derived equations (17), (18) and (22):

$$\theta_f = (\theta_i + \beta) \cdot \exp\left(\frac{I^2 \cdot t}{K^2 \cdot S^2}\right) - \beta. \tag{23}$$

3) Maximum protected length and earth fault loop impedance. The maximum length protected by the protective device to be obtained for a precise instantaneous trip threshold.

   Suppose a bolted earth fault occurs between an active conductor and earth. During such an earth fault, it is desirable that the upstream protective device acts to interrupt the fault within a maximum disconnection time so as to protect against any inadvertent contact to exposed live parts.

To sum up, within mentioned extra conditions which could be verified during dimensioning of the cable not all of them are mandatory. The short-circuit current withstand is one of the main conditions to be checked. Due to that reason in many cases cross-section of the cable which was chosen according to current-carrying capacity and voltage drop shall be increased (not decreased as the current-carrying capacity is the main attribute).

Moreover, it is important always consider number of parallel runs per phase and divide load and short-circuit currents by it as it could lead to mistakes in dimensioning and checking for conditions.

3.4 Flowchart of dimensioning of the cable

In subchapters 3.1-3.3 were presented basic descriptions and algorithms of dimensioning of the cable. In this subchapter all abovementioned steps will be summarized in Figure 18.

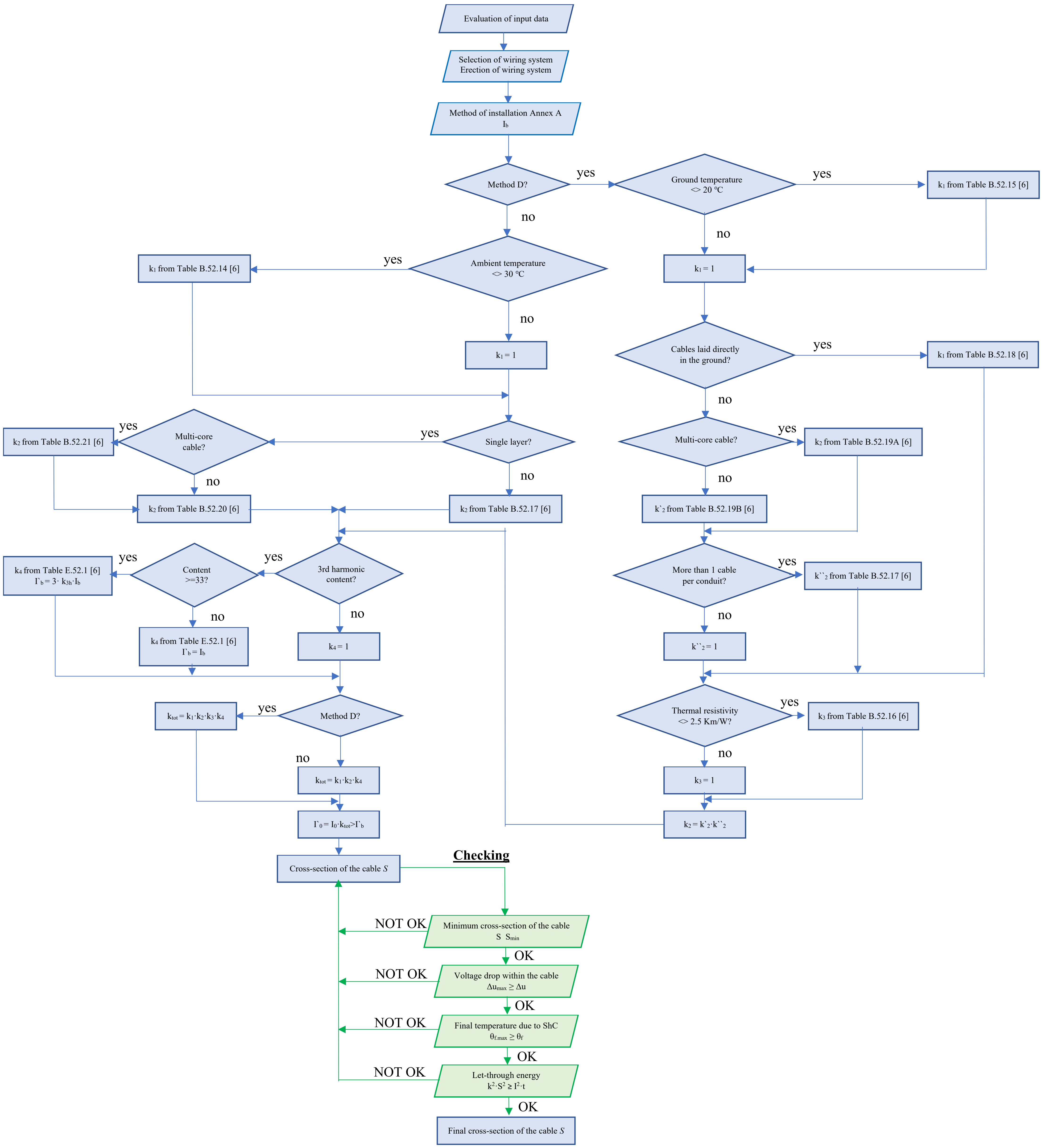


Figure 18 - Flowchart theoretical algorithm of dimensioning of the cable

3.5 Assumptions during calculations of cross-section of the cable

1) Calculations for a group containing different sizes of insulate conductors or cables in conduit systems, cable trunking systems or cable ducting systems which supply same load are not implemented, e.g. group reduction factor. In some non-harmonized (national) standards using of group of insulated conductors or cables with different cross-sections is prohibited, for example in Czech Republic;
2) Choosing of the exact type of the cable from certain manufacturer is not possible to perform, e.g. only calculation of the cross-section and number of parallel runs per tray and trays could be done;
3) The cross-section of neutral conductor is considered to be equal to cross-section of the phase conductor;
4) Initial temperature of the cable within normal operation is calculated based on nominal and based current and not set to be equal only ambient temperature;
5) Calculations of the voltage drop are made for the maximum permitted temperature of the conductor as the worst condition (higher resistance => higher voltage drop);
6) Load considered to be equally distributed between parallel runs and phases;
7) Steel core cables are not considered within calculations. Only copper and aluminium;
8) Considered insulation types correspond to IEC 60364-5-52 Standard, other types of insulations given by manufacturers were not included.

3.6 Recommendations regarding unsatisfied results of dimensioning of the cable

Typically, chosen cross-section of the cable does not satisfy conditions mentioned in previous chapters from the first approach. Instead of increasing or decreasing of cables cross-section minor improvements could be implemented. As many factors are predefined: ambient temperature, length of the cable, conductor material, distance between cables and etc., - and it is not possible to change them, but the following solutions could be considered:

1) Changing of the reference method. For example, from reference method B2 to B1 as B1 is considered for single-core cables and they have higher current-carrying capability and short-circuit current withstand (see Table 4);
2) Changing of the core material. Due to different physical characteristics of the copper and aluminum there are different results in final result of dimensioning of the cable. In case if there is a possibility to change type of the conductor it is highly recommended to use copper.
3) Changing of the type of insulation from PVC to XLPE/EPR type. XLPE/EPR type of insulation has better qualities than PVC one what increase current-carrying capacity of the cable. For example, the maximum permitted temperature of the conductor with XLPE/EPR insulation is 20°C higher than PVC during normal operation (see Table 3);
4) Changing of the arrangement for reference method C, E, F, G. The heat dissipation is different due to different formations and orientation in space of the cables. It cause additional heating of the neighbor cables (described in Chapter 2). Therefore, it leads to decreasing of the current-carrying capacity of the cable by means of changing of derating factor. By considering different types of arrangements (if applicable) the optimal derating factor and therefore cross-section of the cable could be achieved.

3.7 Implementation of algorithm in chosen software

It was decided to choose Microsoft Excel Software for implementation of algorithm described in previous subchapters by using of Visual Basic for Applications (VBA). Implemented algorithm will be described in next subchapters.

The main interface was decided to make based on existing tools from ABB library.

3.7.1 Starting page

Starting Page of a tool could be observed when opening an ExcelBook. There is presented a legenda regarding fields which are necessary to fill in (Figure 19). The way how to come to the procedure of dimensioning of the cable by itself could be done by means of dropdown menu.

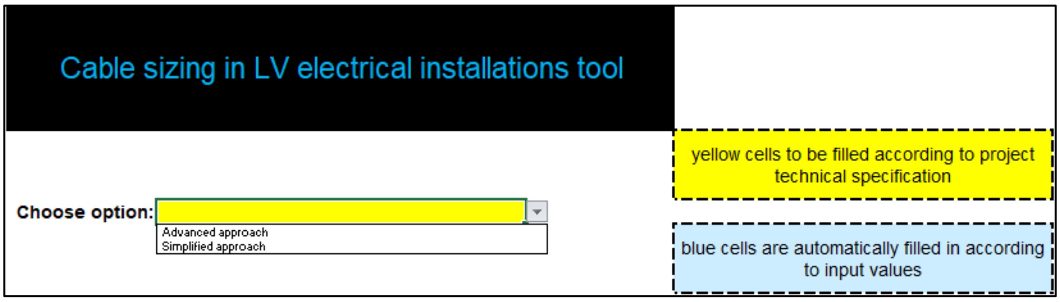


Figure 19 – Starting Page of a Cable Sizing Tool

- **Advanced approach.** Approach is made in accordance with Table A.52.2 of IEC 60364-5-52 Standard [6]. To use it is necessary to know the method of installation of a wiring system and situation concerned (Table 9). It is possible to determine list of examples of methods of installation. When suitable example was chosen, exact reference method can be obtained (Figure 20). For some examples there are extra conditions which are necessary to fill in to obtain reference method (comments are presented in tool).

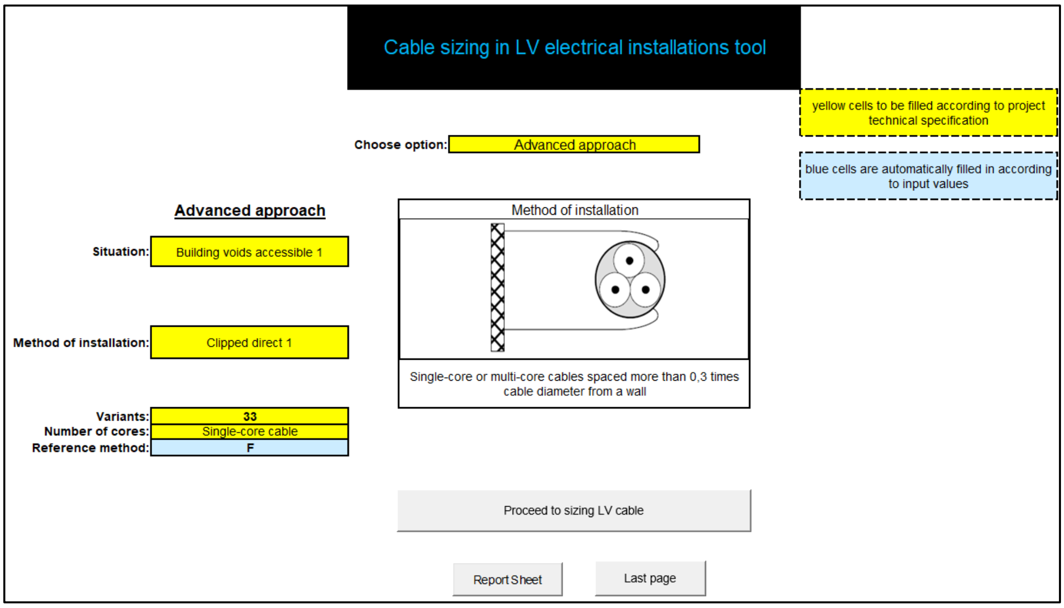


Figure 20 – Example of filled in advanced approach

- **Simplified approach.** Approach is made with a consideration that information about reference method was predefined and it is necessary to determine a list of examples of methods of installation in accordance with Table A.1 (Figure 21).

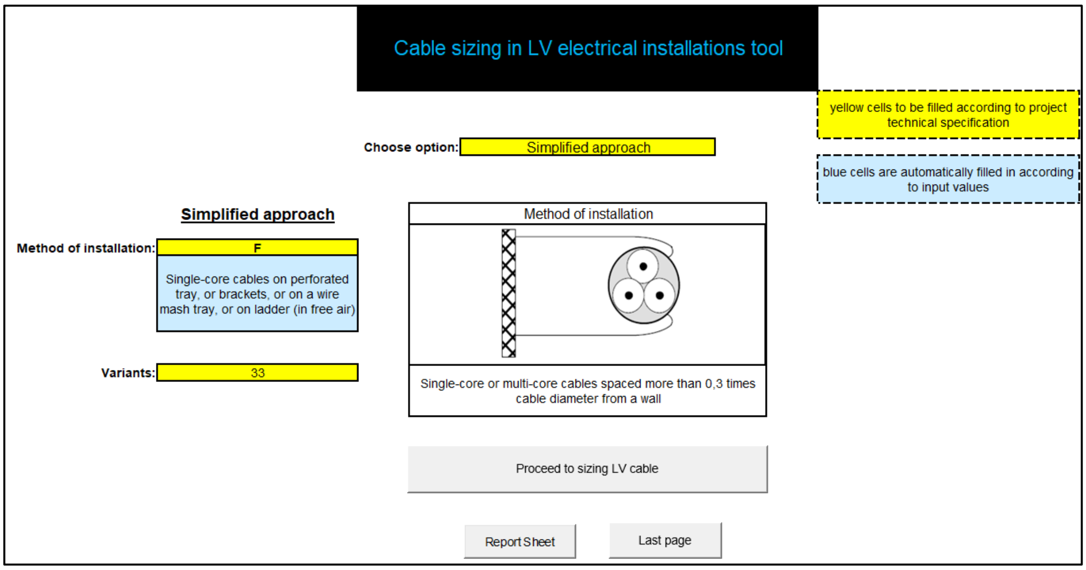


Figure 21 – Example of filled in simplified approach

Additional picture and detailed description for chosen method of installation are given as a clarification. Presented buttons perform following functions:

- **Proceed to sizing LV cable.** Shifting of a working window from starting page to the corresponding reference page;
- **Report Sheet.** Shifting of a working window from starting page to the report page;
- **Last page.** Shifting of a working window from starting page to the last activated page.

3.7.2 Reference method page

By clicking a button “Proceed to sizing LV cable” an interface will be shifted from “Start” page to a page which refers to chosen method (Figure 22).

Reference method page consist of all necessary information for sizing cable according to IEC 60364-5-52 Standard [6]. This information was described in details in previous chapters and can be distinguished by following:

1) Legenda which is describing the meaning of cells colors;
2) Basic information regarding switchgear to which cable belongs;
3) Information about chosen reference method and method of installation;
4) Definition of type of feeder (motor or common) and load given data. Type of feeder is needed only due to additional checking conditions for motors. Load given data was described in subchapter 3.1.1;
5) Cable given data. Was described in subchapter 3.1.2;
6) Clarification for voltage drops;
7) An option for considering of harmonic content by means of “Enable” check box (see subchapter 3.1.2, point 5);
8) Result of dimensioning of the cable;
9) Checking conditions.

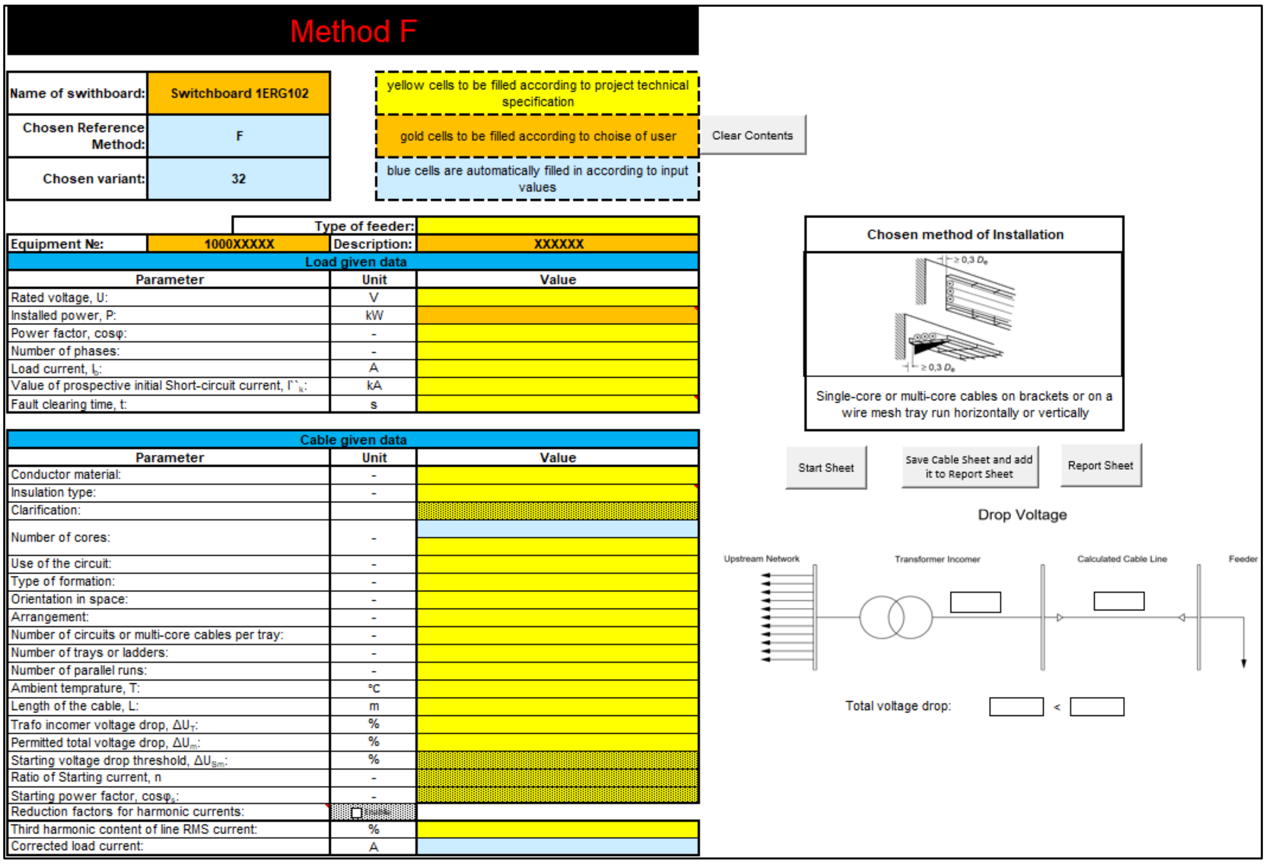


Figure 22 – Reference method page (method F)

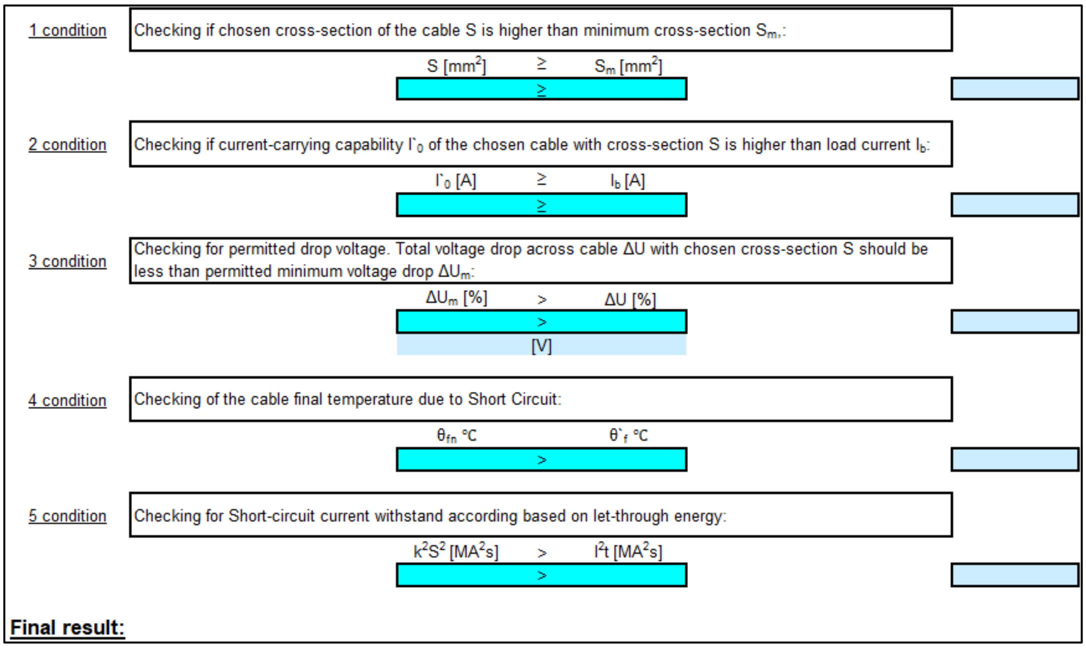


Figure 23 – Conditions for checking of the cables cross-section

Besides tables and pictures there are presented additional buttons with following functions:

- **Clear contents.** Clear all cells for a new dimensioning;
- **Start Sheet.** Shifting of a working window from reference method page to the start page;
- **Save cable sheet and add it to report sheet.** Saving of the cable sheet as a new one and adding necessary input and output information to report sheet (will be described in later chapters);

- **Report sheet.** Shifting of a working window from starting page to the report page;
- **Show result.** Showing the cross-section of the cable which satisfies all conditions.

Conditions for checking of the cables cross-section are presented on Figure 23 correspond with conditions presented in Figure 18.

As input data is filled in (Figure 22), conditions are checked (Figure 23) result could be obtained. Information regarding if cross-section of cable is satisfied to all conditions is presented in "Final result" row. After cross-section of cable is defined it is possible to save a datasheet of sized cable by "Save cable…" button. By clicking the button following window could be seen:

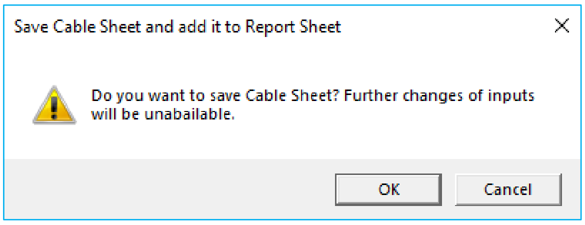


Figure 24 – "Save cable sheet and add it to report sheet" click button result

In case if it is necessary to make changes within calculations press the "Cancel" button, otherwise press the "OK" button.

After clicking the button "OK" following window could be seen:

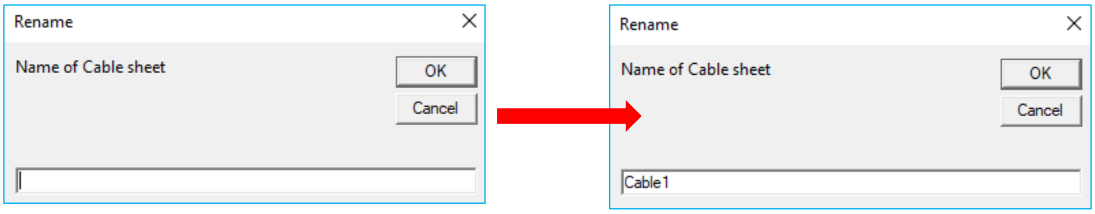


Figure 25 – Renaming of reference method page

Within suggested window it is possible to rename a copy of the Reference Method page. For example, from "Method F" to "Cable1" (Figure 25). By clicking the button "Cancel" it is still possible to come back to calculations, otherwise window presented on Figure 26 could be observed.

Some buttons which serve for better navigation within tool and page and for operations with a report table and main parameters (results of calculation): input data, correction factors, outputs - are presented on a "Report sheet". As some definitions are pretty long (arrangement) was decided to create additional table with clarifications for such cases (Annex B).

The example with calculations: filled in tables, checking for conditions, final result, additional functions of the tool – will be presented in chapter 4.

Despite that tool was done based on IEC 60364-5-52 Standard, additional literature and considering flowchart presented on figure 18 there are some exclusions. Description of the implemented algorithm will be given in the next chapter.

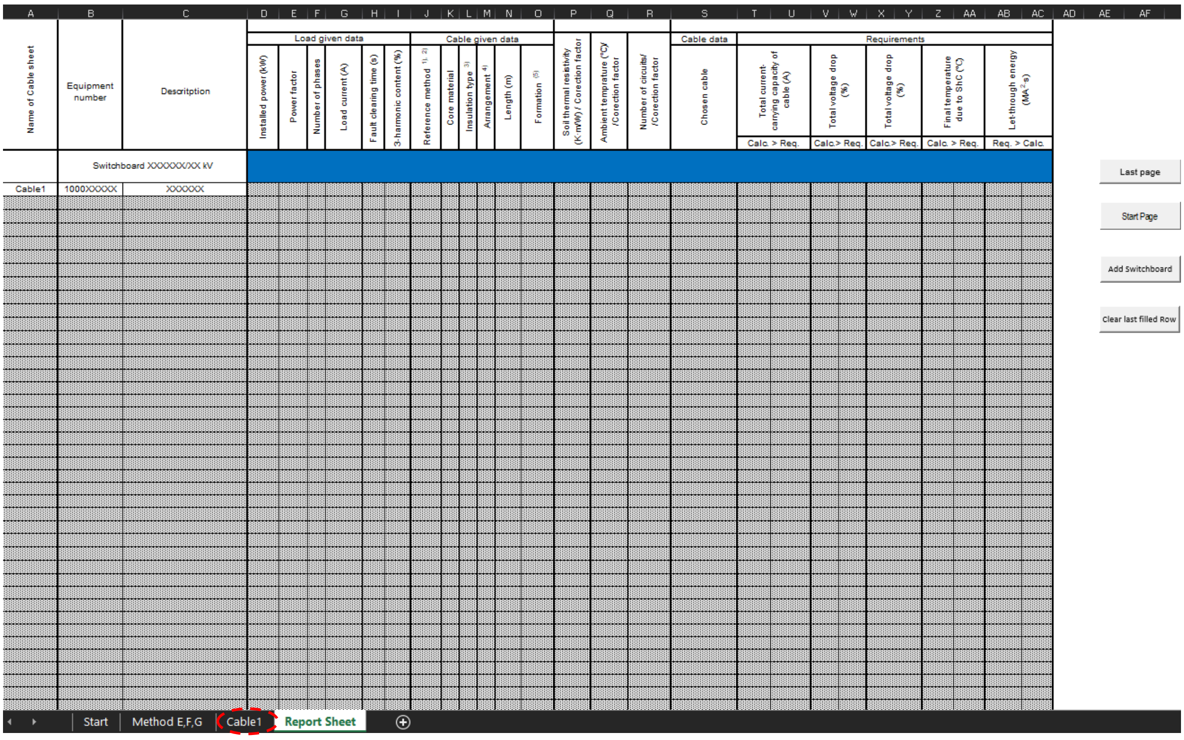


Figure 26 – View on the "Report Sheet"

3.8 Practical algorithm for dimensioning of the cable

Generally speaking, there are no significant differences between theoretical algorithm which was described before and implemented one. Steps 1-8 from subchapter 3.2 are the same for both algorithms, but applied checking conditions and a way how the final result is obtained are needed to be described. The input data processing starts right after all necessary cells (Load given data, Cable given data) were filled in. The process looks as following:

- Based on chosen reference method (including special cases like orientation in space, formation and etc.), core material insulation type the tool finds proper column in corresponding table. By applied filters tool starts to search in corresponding column minimum cross-section (S_1) which nominal current-carrying capacity considering correction factors is higher than load current. Similar to step 9 in subchapter 3.2 (8);
- Calculation of voltage drop for all available cross-sections and then searching for minimum cross-section (S_2) with which voltage crop and current-carrying capacity conditions are satisfied. In case if motor feeder type was chosen additional checking for starting voltage drop is applied as well and additional search for cross-section is done (S_2`);
- Calculation of final temperature of the cable due to short-circuit current for all available cross-sections and find the minimum cross-section (S_3) with which final temperature and current-carrying capacity conditions are satisfied;
- Calculation of the let-through energy for all available cross-sections and find the minimum cross-section (S_4) with which let-through energy and current-carrying capacity conditions are satisfied;
- Comparison of all found cross-sections (S_1, S_2, S_2`, S_3 and S_4) and choosing the maximum one as it shall satisfy all conditions in the same time. Usually minimum cross-section due to mechanical reasons lower than others. Practical algorithm for dimensioning of the cable is presented in simplified flowchart (Figure 27).

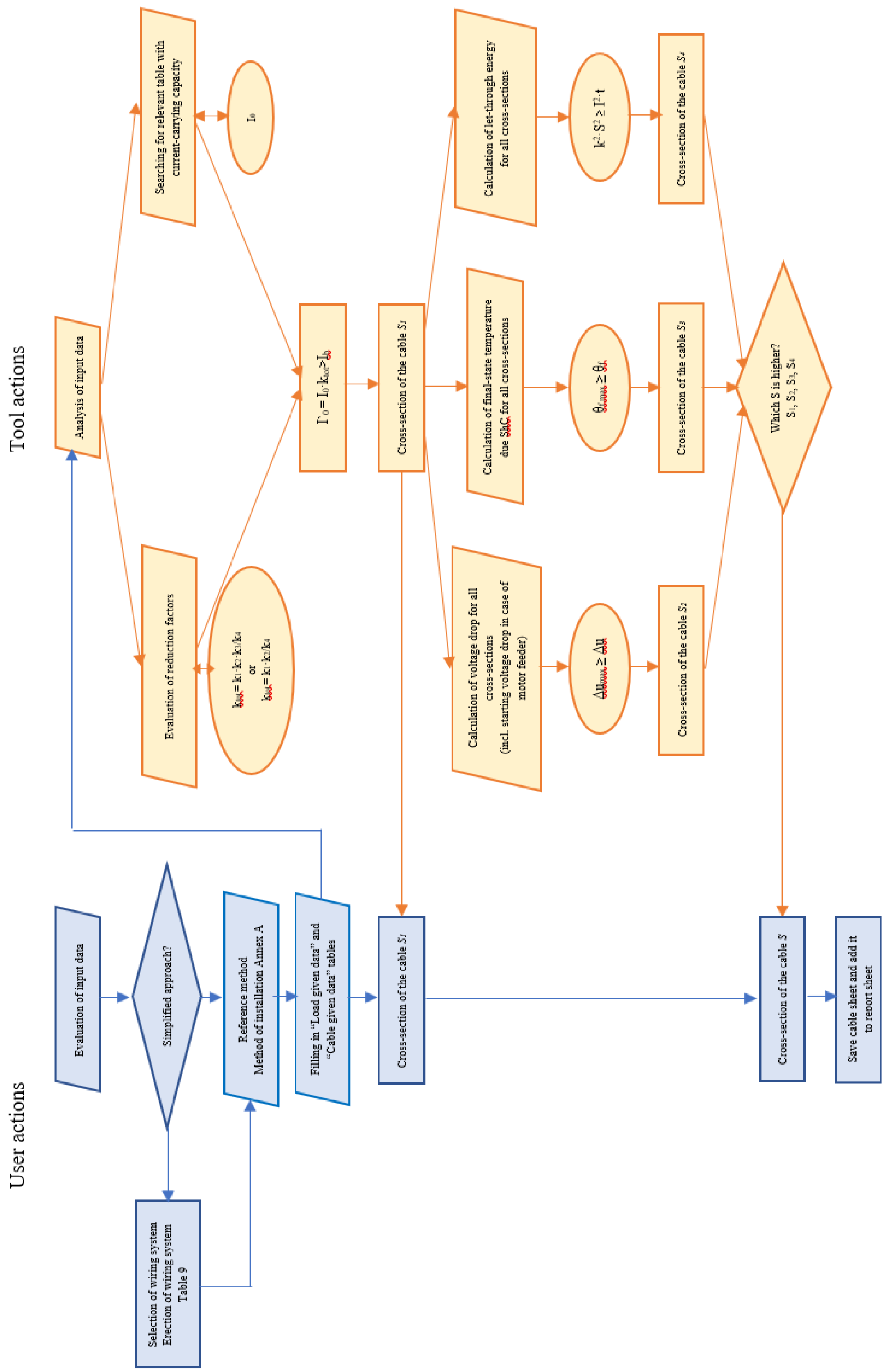


Figure 27 - Practical algorithm for dimensioning of the cable flowchart

4 Verification of the Correct Functionality of the Created Algorithm on Practical Examples

4.1 Examples of calculations

The practical examples which includes common cases of the tool based on implemented algorithm for dimensioning of the LV cable described in previous chapter are shown below.

4.1.1 Example №1

Dimensioning of a cable with following load characteristics:

- Reference Method : E/31
- Type of feeder : Motor load
- Rated voltage : 400 V
- Power factor : 0.83
- Number of phases : 3
- Rated size (input power) : 60 kW
- Prospective initial Short-circuit current : 31.2 kA
- Fault clearing time : 0.2 s

Cable and installation conditions:

- Conductor material : Copper
- Insulation type : EPR
- Description of a dimensioning cable : 2 multi-core (3C+PEN) cables
- Installation : cables bunched on perforated tray
- Ambient temperature : 25 °C
- Length of cable : 95 m
- Permitted total voltage drop : 5 %
- Transformer incomer voltage drop : 1.24 %
- Starting voltage drop threshold : 17%
- Ratio of Starting current : 5 p.u.
- Starting power factor : 0.39
- Adjacent circuit with : a) three-phase circuit consisting of 4 single-core cables, 4x50 mm^2;

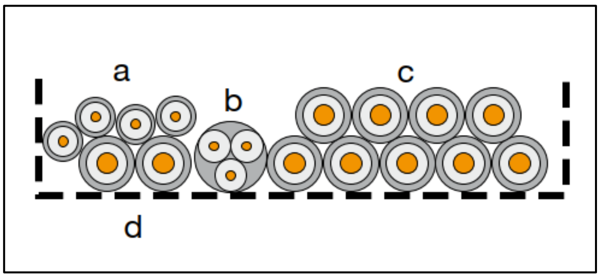


Figure 28 – Installation for Example 1

b) three-phase circuit consisting of one multi-core cable, 1x(3x50) mm^2;

c) three-phase circuit consisting of 9 single-core (3 per phase) cables, 9x95 mm^2;

d) single-phase circuit consisting of 2 single-core cables 2x70 mm^2.

As a first step, the number of circuits or multi-core cables present shall be determined, given that:

- each circuit a), b) and d) constitute a separate circuit;
- circuit c) consists of three circuits, since it is composed by three cables in parallel per phase;
- the cable to be dimensioned is 2 multi-core cables in parallel and therefore constitutes two circuits;

The total number of circuits is 8.

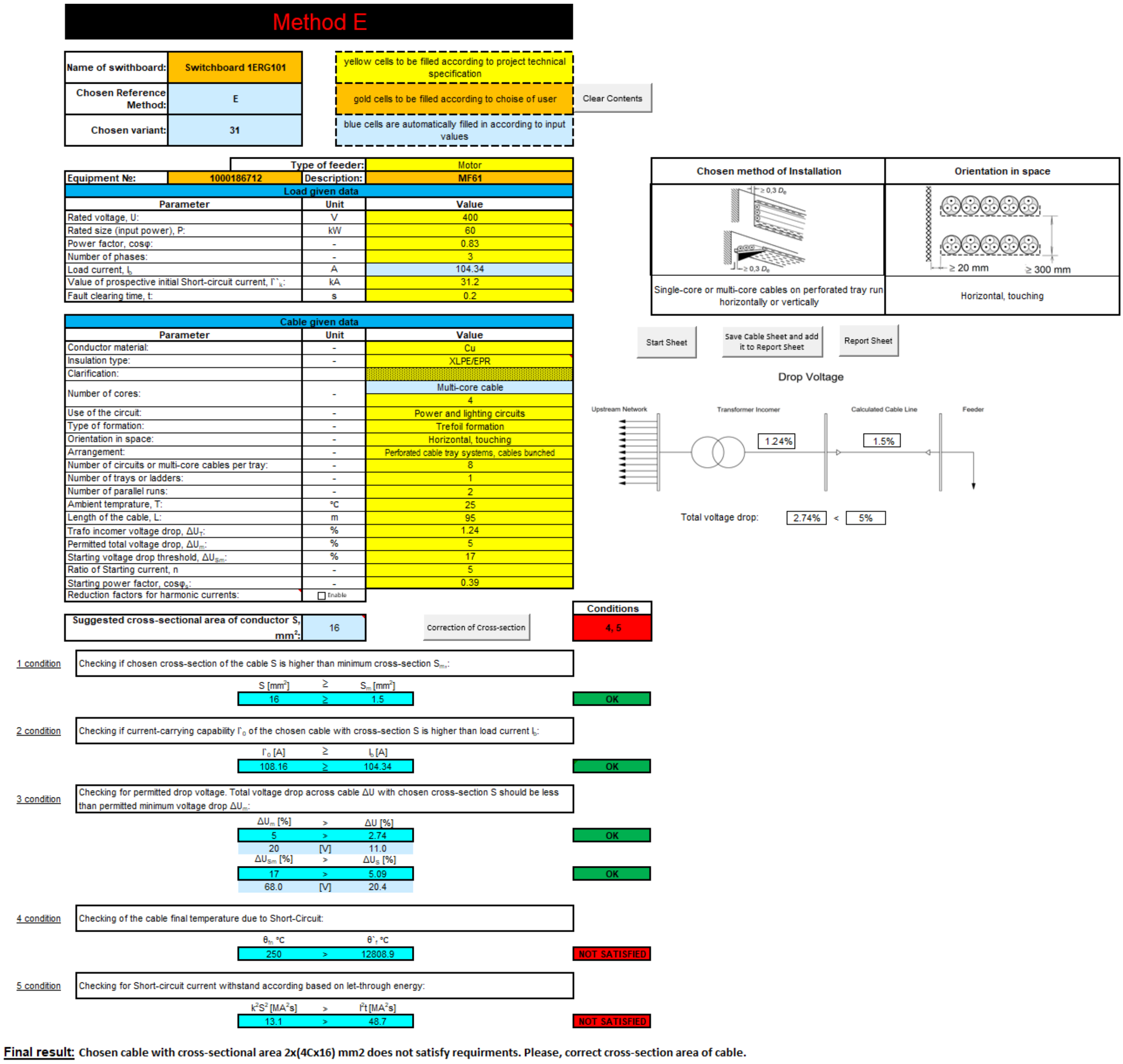


Figure 29 – Inputs and results for example №1

As it could be observed, first obtained result does not satisfy 4th and 5th conditions. It was suggested at first to satisfy condition 1 and 2 (see Figure 27). After pressing the button "Correction of Cross-section" following cross-section could be obtained:

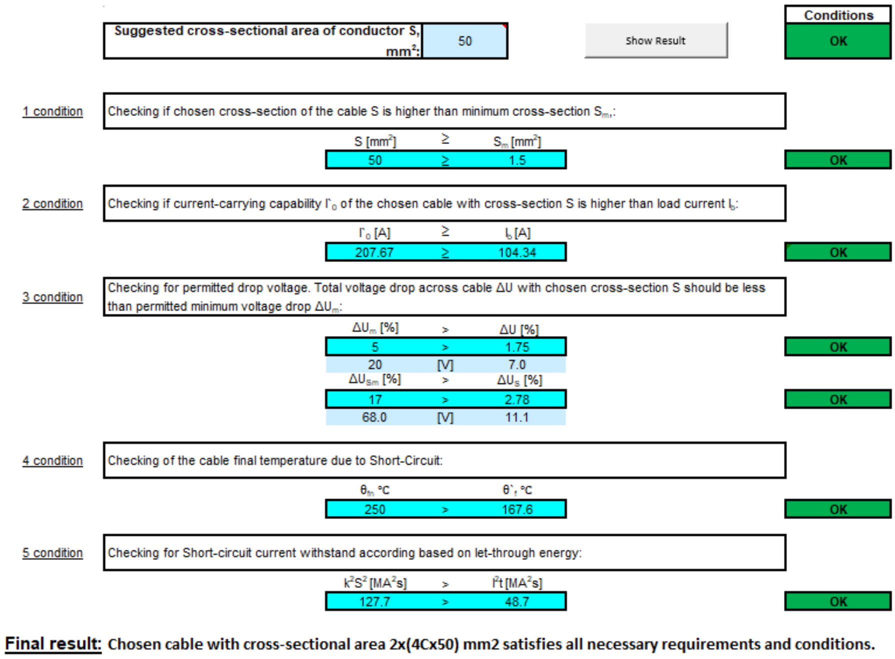


Figure 30 – Final results for example №1

New proposed cross-section of the cable satisfies all necessary conditions. It could be saved to report sheet. The table with all sized cables will be presented when all examples will be shown.

It is important to mention that dimensioning of the cable is done after short-circuit analysis were performed but selection of protective devices was not done yet. The meaning is that the cable was probably oversized to satisfy conditions 4 and 5 to withstand the maximum short-circuit time within fault clearing time and to be not damaged.

After selection of protective devices was done, the cross-section of the cable could be checked for all conditions again and in case if lower cross-section is suggested, it could be chosen as the final cross-section of the cable.

4.1.2 Example №2

Case a) Dimensioning of the cable not considering third harmonic content:

Dimensioning of a cable with following load characteristics:

- Reference Method : D/70
- Type of feeder : Passive load
- Rated voltage : 690 V
- Power factor : 0.87
- Number of phases : 3
- Rated power : 250 kW
- Prospective initial Short-circuit current : 21.2 kA
- Fault clearing time : 0.15 s

Cable and installation conditions:

- Conductor material : Copper
- Insulation type : PVC
- Description of a dimensioning cable : 3 multi-core (3C+PEN) cables, 1 per 1 duct
- Installation : In conduit in the ground
- Duct to duct clearance : 1 m
- Ambient temperature : 20 °C
- Length of cable : 60 m

- Permitted total voltage drop : 5 %
- Transformer incomer voltage drop : 0.5 %
- Third harmonic content (Case b) : 16%
- Adjacent circuit with : -

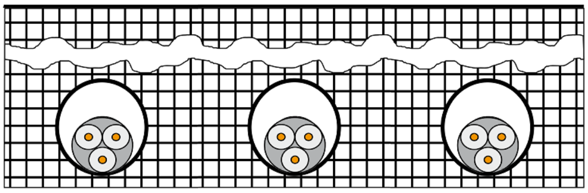


Figure 31 – Installation for Example №2

In case of reference method D1 it is necessary to specify number of circuits per conduit. In our case we have one circuit per one conduit and impaction of other cables are considered by means of duct to duct clearance. Results of calculations are presented on following figures:

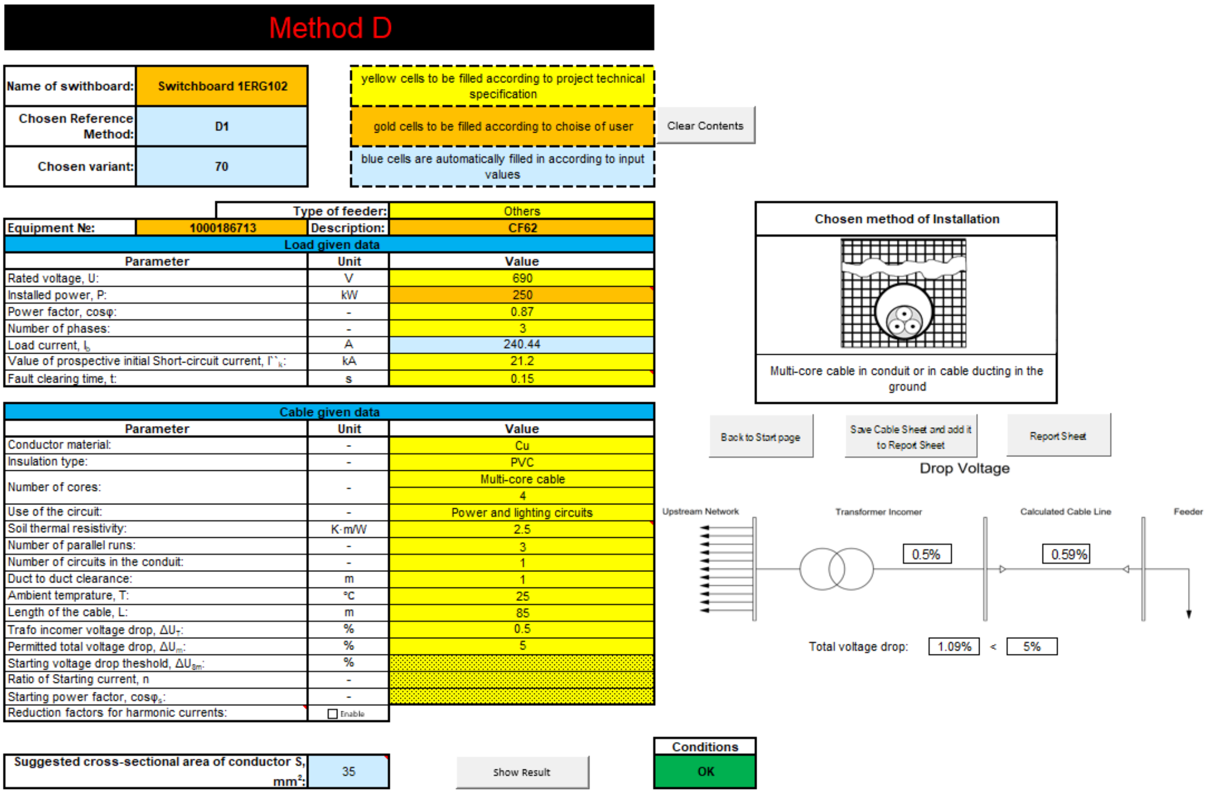


Figure 32 – Inputs for Example №2 Case a)

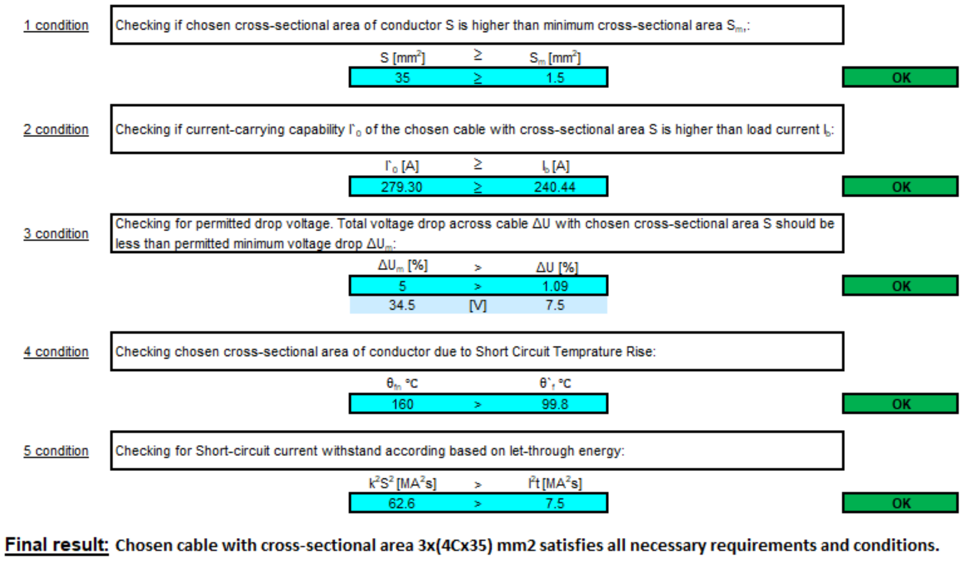


Figure 33 – Results for Example №2 Case a)

As it could be observed, first obtained result satisfies all necessary conditions unlike example 1. It could be explained by means of high rated power of a consumer therefore high load currents. Nevertheless, withstand due short-circuit current is achieved with high margin and cross-section could be decreased. However, satisfying of 2nd condition (current-carrying capacity) has higher priority than others so decreasing of cross-section is not allowed. It could be saved to report sheet.

Case b) Dimensioning of the cable considering third harmonic content

During following calculations, the same inputs as in Case a) will be considered except that fact that third harmonic content in this case is equal 16%.

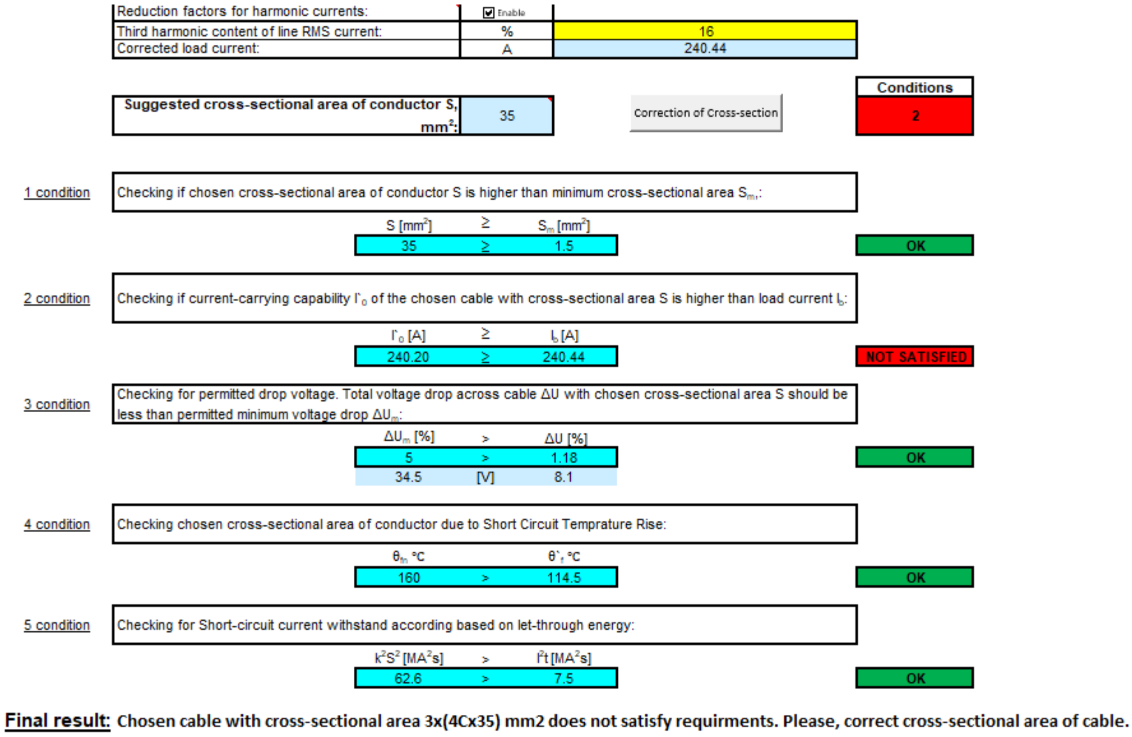


Figure 34 – Checking of result from Example №2 Case a) for Case b)

As it could be seen from Figure 34 that the result obtained in Case a) does not satisfy 2nd condition due to third harmonic content but with very tight margins. To fulfill this condition and to be on a "safe" side it is necessary to proceed calculations again (see Figure 35).

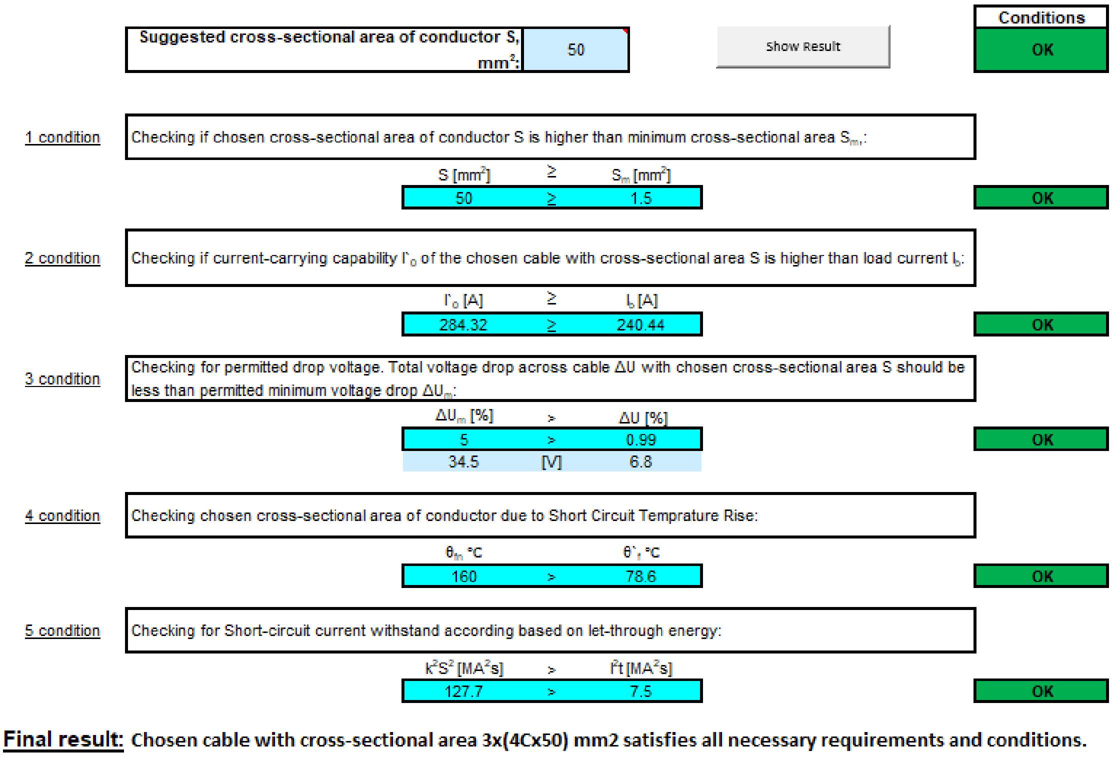


Figure 35 - Results for Example №2 Case b)

As could be seen from Figure 35 that in Case b) when third harmonic is considered cross-section of dimensioning cable was increased from 35 mm^2 to 50 mm^2 to satisfy 2nd condition but available current-carrying capacity increased not that much in comparison with Case a). However, as in this case 2nd condition is not satisfied only with digits numbers, it is upon a user (engineer) to decide which cross-section to choose as the final one. Nevertheless, other conditions satisfied with "safe" margins for both options.

4.1.3 Example №3

Dimensioning of a cable with following load characteristics:

- Reference Method : A2/2
- Type of feeder : Passive load
- Rated voltage : 230 V
- Power factor : 0.75
- Number of phases : 1
- Load current : 60 A
- Prospective initial Short-circuit current : 16.6 kA
- Fault clearing time : 0.1 s

Cable and installation conditions:

- Conductor material : Copper
- Insulation type : PVC
- Description of a dimensioning cable : 1 multi-core (1C+PEN) cable
- Installation : In conduit in thermally insulated wall
- Ambient temperature
- Length of cable : 30 °C
- Permitted total voltage drop : 75 m
- Transformer incomer voltage drop : 5 %

: 1.24 %

- Adjacent circuit with : a) single-phase circuit consisting of 2 single-core cables, 2x35 mm^2;

  b) three-phase circuit consisting of one multi-core cable, 1x(3x50) mm^2;

  c) three-phase circuit consisting of 3 single-core cables, 3x70 mm^2;

  d) three-phase circuit consisting of one multi-core cable 1x(3x16) mm^2.

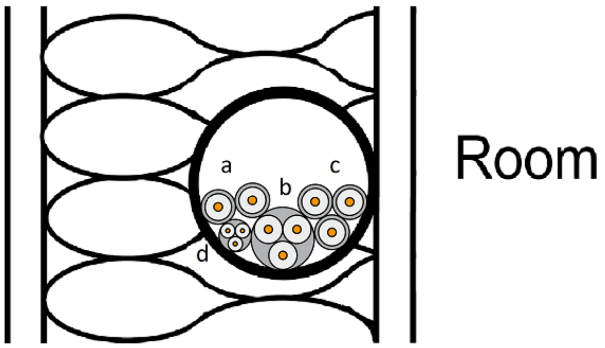
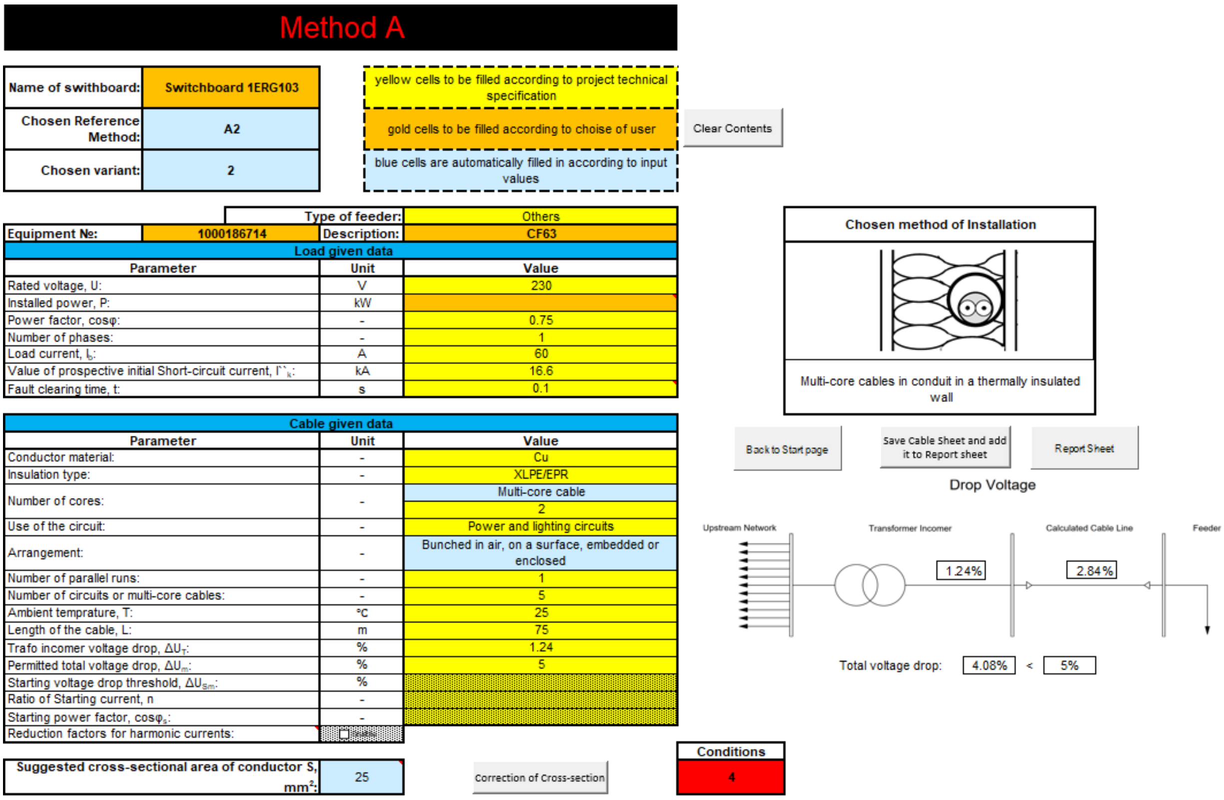


Figure 36 – Installation for Example №3

As a first step, the number of circuits or multi-core cables present shall be determined, given that:

- each circuit a), b), c) and d) constitute a separate circuit;
- the cable to be dimensioned is a multi-core cables in parallel and therefore constitutes one circuit.

The total number of circuits is 5.



Method A

Name of swithboard:	Switchboard 1ERG103
Chosen Reference Method:	A2
Chosen variant:	2

yellow cells to be filled according to project technical specification

gold cells to be filled according to choise of user

blue cells are automatically filled in according to input values

Clear Contents

		Type of feeder:	Others
Equipment №:	1000186714	Description:	CF63

Load given data		
Parameter	**Unit**	**Value**
Rated voltage, U:	V	230
Installed power, P:	kW	
Power factor, cosφ:	-	0.75
Number of phases:	-	1
Load current, I_b:	A	60
Value of prospective initial Short-circuit current, I''_k:	kA	16.6
Fault clearing time, t:	s	0.1

Cable given data		
Parameter	**Unit**	**Value**
Conductor material:	-	Cu
Insulation type:	-	XLPE/EPR
Number of cores:	-	Multi-core cable 2
Use of the circuit:	-	Power and lighting circuits
Arrangement:	-	Bunched in air, on a surface, embedded or enclosed
Number of parallel runs:	-	1
Number of circuits or multi-core cables:	-	5
Ambient temprature, T:	°C	25
Length of the cable, L:	m	75
Trafo incomer voltage drop, ΔU_T:	%	1.24
Permitted total voltage drop, ΔU_m:	%	5
Starting voltage drop threshold, ΔU_{Sm}:	%	
Ratio of Starting current, n	-	
Starting power factor, $\cos\varphi_s$:	-	
Reduction factors for harmonic currents:		

Suggested cross-sectional area of conductor S, mm^2:	25

Correction of Cross-section

Conditions
4

Chosen method of Installation

Multi-core cables in conduit in a thermally insulated wall

Back to Start page

Save Cable Sheet and add it to Report sheet

Report Sheet

Drop Voltage

Upstream Network

Transformer Incomer

Calculated Cable Line

Feeder

1.24%

2.84%

Total voltage drop: 4.08% < 5%

Figure 37 – Inputs for example №3

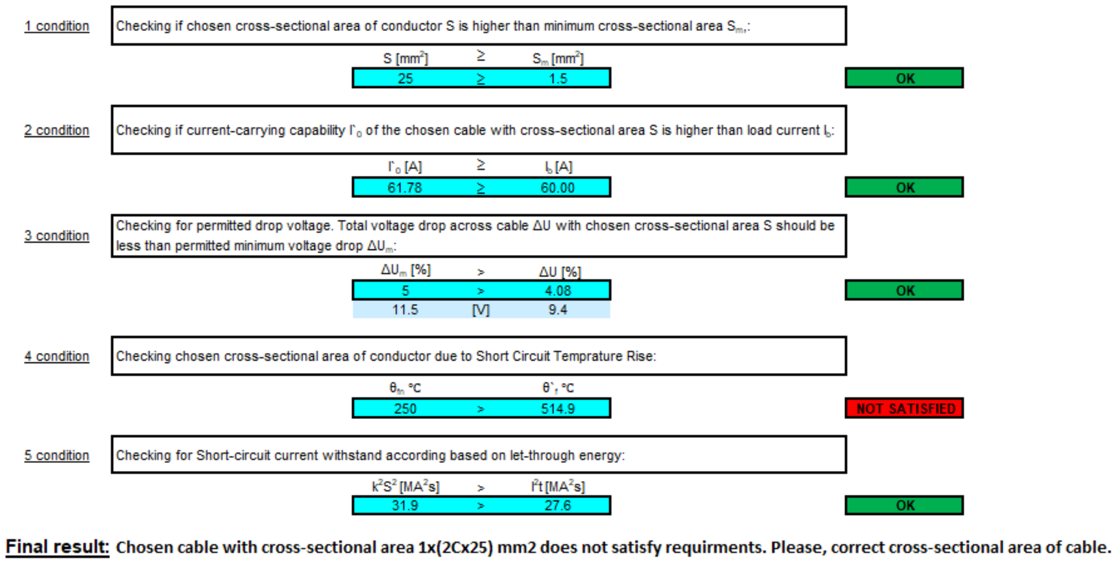


Figure 38 – Results for example №3

First obtained result does not satisfy 4th condition only. Again, it was suggested at first to satisfy condition 1 and 2 (see Figure 38). Nevertheless, the cross-section of 25 mm^2 is very tie for all conditions and almost in "safe" margins to satisfy them.

After pressing the button "Correction of Cross-section" following cross-section is obtained:

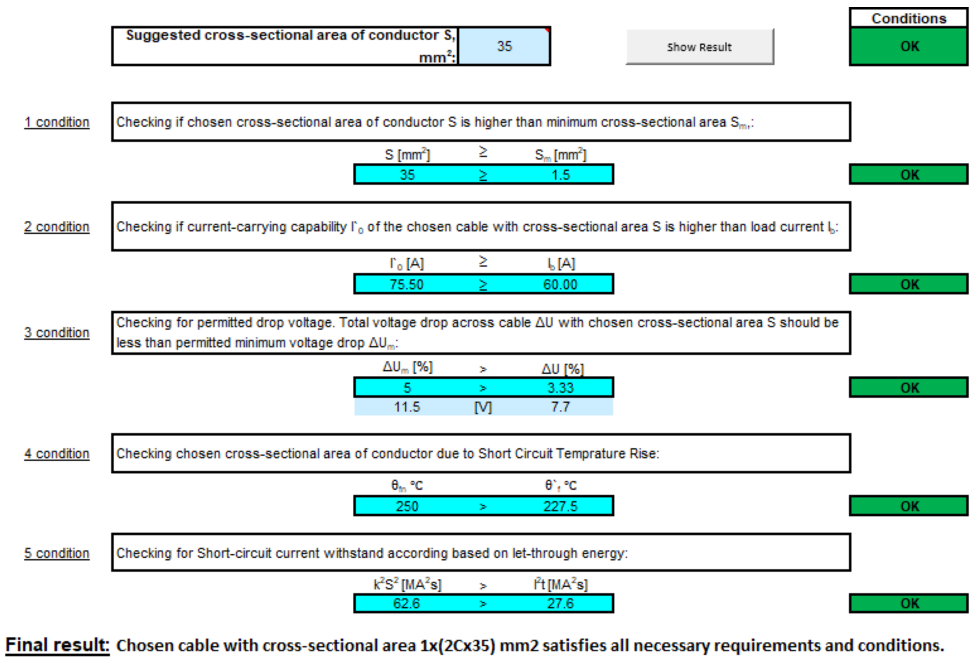


Figure 39 – Final results for example №3

New suggested cross-section of the calculated cable satisfy all necessary conditions. It could be saved to report sheet.

The thing which should be considered if suggested cross-section of cable will fit in conduit. But it is out of scope of this diploma thesis.

4.1.4 Example №4

Dimensioning of a cable with following load characteristics:

• Reference Method	:	F/32
• Type of feeder	:	Passive load
• Rated voltage	:	690 V
• Power factor	:	0.9
• Number of phases	:	3
• Rated power	:	1 MW
• Prospective initial Short-circuit current	:	23.2 kA
• Fault clearing time	:	0.15 s

Cable and installation conditions:

• Conductor material	:	Copper
• Insulation type	:	XLPE
• Description of a dimensioning cable	:	2x3 (6) single-core cables
• Installation	:	Cable ladder system
• Ambient temperature	:	20 °C
• Length of cable	:	50 m
• Permitted total voltage drop	:	5 %
• Transformer incomer voltage drop	:	2.32 %
• Adjacent circuit with	:	-

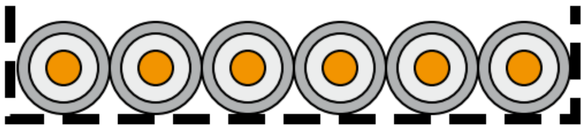


Figure 40 – Installation for Example №4

The total number of circuits is 2.

This example is for high power feeder. In this case single-core cables are more suitable as they have higher nominal current-carrying capabilities [6] and better withstand influence of short-circuit current. The major factor which impact on decision whether to use multi-core or single-core cable is economical aspect [7].

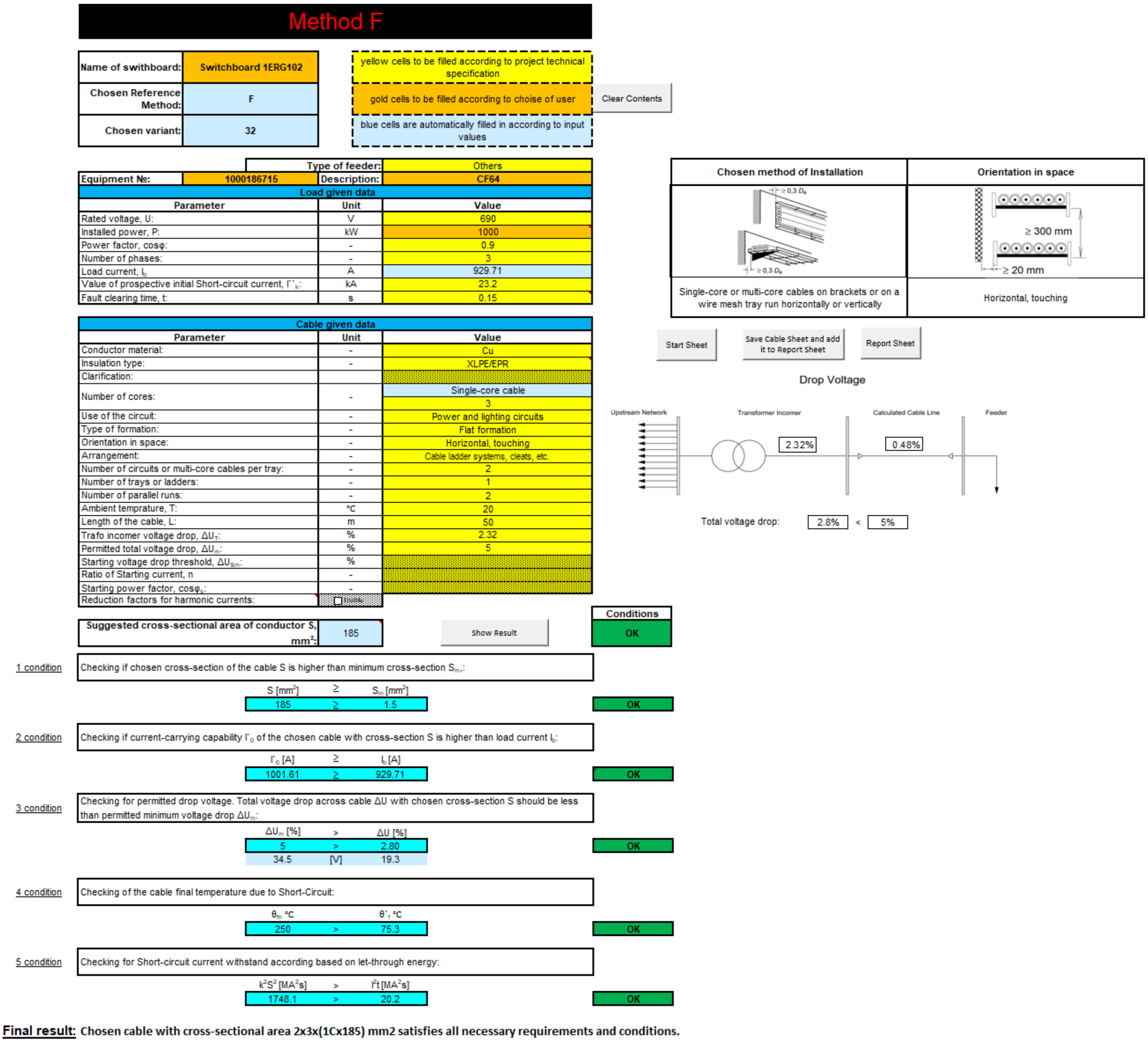


Figure 41 – Inputs and results for example №4

First obtained result satisfies all necessary conditions same as example №2. Again, satisfying of 2nd condition (current-carrying capacity) has higher priority than others so decreasing of cross-section is not allowed even if other conditions are satisfied with high margins. It could be saved to report sheet (Figure 42).

4.2 Evaluation of results

Small remarks regarding examples were given after each calculation. However, based on obtained results from previous subchapter it is possible to sum up following general statements:

1) Important to repeat that cross-sections were suggested based on maximum proposal initial short-circuit current. It was done in this way due to assumption that selection of protective devices is done as the next step after dimensioning of the cable. After it, cross-section could be recalculated and decreased or stayed the same;

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
			Input data												Derating factors			Output data										
			Load given data						Cable given data									Cable data	Requirements									
Name of Cable sheet	Equipment number	Descritption	Installed power (kW)	Power factor	Number of phases	Load current (A)	Fault clearing time (s)	3-harmonic content (%)	Reference method 1), 2)	Core material	Insulation type 3)	Arrangement 4)	Length (m)	Formation (5)	Soil thermal resistivity (K·mW) / Corection factor	Ambient temprature (°C)/ Corection factor	Number of circuits/ Corection factor	Chosen cable	Total current-carrying capacity of cable (A)		Total voltage drop (%)		Total starting voltage drop (%)		Size due to ShC temprature rise (mm^2)		Let-through energy (MA^{2}s)	
																			Calc. > Req.		Calc.> Req.		Calc.> Req.		Calc. > Req.		Req. > Calc.	
		Switchboard 1ERG101/0.4 kV																										
Example1	1000186712	MF61	60	0.83	3	104.34	0.2		E/31	Cu	2	18	95	1		25/1.04	1x8/0.52	2x(4Cx50)	207.7	104.34	5	1.75	17	5.09	250	167.7	127.69	48.67
		Switchboard 1ERG102/0.69 kV																										
Example2A	1000186713	CF62	250	0.87	3	240.44	0.2		D1/70	Cu	1	9	85		2.5/1	25/0.95	1/1	1x(4Cx35)	279.3	240.44	5	1.09			160	99.8	62.568	7.491
Example2B	1000186713	CF62	250	0.87	3	240.44	0.2	16	D1/70	Cu	1	9	85		2.5/1	25/0.95	1/1	1x(4Cx50)	284.3	240.44	5	0.99			160	78.6	127.7	7.491
Example4	1000186715	CF64	1000	0.9	3	929.71	0.2		F/32	Cu	2	15	50	2		20/1.08	1x2/0.87	2x3x(1Cx185)	1002	929.71	5	2.8			250	227.5	1748.1	20.18
		Switchboard 1ERG103/0.23 kV																										
Example3	1000186714	CF63		0.75	1	60.00	0.1		A2/2	Cu	2	1	75			25/1.04	5/0.6	1x(2Cx35)	75.5	60.00	5	3.33			250	70.3	62.568	27.56

Figure 42 – Report sheet with results of all example

2) Examples 2 and 4 show that not in all cases short-circuit withstand is the worst condition. Load current plays the major role during checking of the cables and should be satisfied no matter what;
3) Example 4 is a great example that number of parallel runs is a crucial from the point of view of the dimensioning of the cable. To have 6 single-core cables with cross-section 185 mm^2 (2 parallel runs) is a huge investment. If it is possible, increasing of number of parallel runs could be an option, it will lead to decreasing of cross-section of the cable;
4) Example 1 shows that higher number of circuits within one tray, ladder or duct has significant impact on current-carrying capacity of the cable (see Figure 42, corresponding row to example 1);
5) Example 4 shows that insulation material has important meaning during dimensioning of the cable. If in mentioned example insulation material was PVC, chosen cross-section would not satisfy 4^{th} condition and 240 mm^2 would be suggested. It would lead to higher economical investments.

In case if chosen cross-section of the cable doesn't satisfy always important to remember recommendations which were given in subchapter 3.6, apply them and recalculate till that moment when suitable (speaking not about conditions, but personal demand: maximum allowed cross-section, insulation material and etc.) cross-section is obtained.

4.3 Potential for further developing of the tool

Even if tool was made in sufficient way for dimensioning of the LV cable, following improvements could be considered:

1) Appearance of the tool:
   1.1) Improving of structure of the "Load given data" and "Cable given data" tables;
   1.2) Adding of clear comments to cells with corresponding instructions or appropriate values in case of exact input values is unknown.
2) Coding aspect:
   2.1) Optimization of the written code for better and quicker operation of the tool;
   2.2) Consideration of developing of the tool in another suitable software.
3) Improvements in calculations and algorithm:
   3.1) Extending of the tool with several types of protective devices for better sizing of the cable according to short-circuit current withstand;
   3.2) In case if step 3.1 was implemented, consideration of adding selectivity chart for clarification;
   3.3) Implementation of several more checking conditions such as: maximum protected length of the cable [7], automatic disconnection time depends on earthing system [16], protection against overload [7, 16], economical calculations (the less priority);
   3.4) Detailed clarification of the number of circuits and number of parallel runs, especially for reference methods D, E, F;
   3.5) Implementation of the sizing of the cable considering total harmonic distortion (THD) in case of sizing cable for inverters/converters, and for periodic loads considering duty cycles of the motor [17].

Conclusion

During work on this diploma was performed deep analysis of IEC 60364-5-52 Standard which regulate the selection and erection of low voltage wiring systems (cables) and related study materials. As the main outcome of these researches could be mentioned following statements:

- Analysis of failures in power networks caused by breakdown of cables and related accidents and as the result formulation of important conditions for correct dimensioning of low voltage cables. Moreover, list of negative consequences if such conditions are not followed;
- Investigation of IEC 60364-5-52 Standard and related study materials with the aim of detailed description of theoretical background of dimensioning of low voltage;
- Formulation of theoretical algorithm which could be followed for correct dimensioning of the low voltage cable considering calculations by itself and based on it development of simplified practical algorithm which could be implemented in chosen software (MS Excel with help of VBA) and its implementation;
- Performance of examples which show correct functionality of developed algorithm and tool and evaluation of obtained results.

Even if the result of done work may be classified as a successful one needless to say that there are still thing which could be improved:

- Assumptions which were made for easier implementation of practical algorithm in medium of chosen software and which were not clear from reviewed sources should be investigated more in details and added to algorithm or deleted at all;
- Extension of the tool with more calculations for fulfilling additional conditions which were described in this thesis due to fulfill of all aspects of dimensioning of the low voltage cables. Considering extension of the tool not only with cable sizing but with protection devices and selectivity as well for adequate results;
- Investigation of standards related to medium and high voltages for covering of all levels of voltage and be able to perform such calculations.

Nevertheless, during work on this thesis many skills which correspond to an engineer were obtained: understanding of basic and more advanced problems connected to dimensioning of the low voltage cables, ability to be focused on formulated problem, correct evaluation of result of the performed work, ability to work with European standards and normative and getting from there important and necessary information, knowledge in basic programming in MS Excel which helped for implementation of developed algorithm.

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